STATE OF THE ART REPORT 5

Reactions, Properties, Design, and Construction

TRANSPORTATION RESEARCH BOARD
National Research Council

Contents

Introduction

For many years, various forms of lime, including products with varying degrees of purity, have been utilized successfully as soil stabilizing agents. However, hydrated high calcium lime $Ca(OH)_2$, monohydrated dolomitic lime $Ca(OH)_2 \cdot MgO$, calcitic quicklime CaO, and dolomitic quicklime $CaO \cdot MgO$ are most frequently used. Although lime hydrates dominate the U.S. market, quicklime use has increased over the past 20 years and currently accounts for 25 percent of the total stabilization lime on an annual basis.

Many significant engineering properties of soils are beneficially modified by lime treatment. Although lime is primarily utilized to treat fine-grained soils, it can also be used to modify the characteristics of the fine fraction of more granular soils. Lime treatment can expedite construction, modify subgrade soils, and improve strength and durability of fine-grained soils.

Lime-treated soils have been used as modified subgrades, subbase materials, and base materials in pavement construction. The location of the lime-treated layer in the pavement system is dictated by strength, durability, and other design criteria. Railroad subgrades have also been successfully stabilized with lime.

The state of the art in lime treatment based on a comprehensive analysis of current practice and technical literature is presented in this report. References are included for more information. Originally prepared by the Transportation Research Board Committee on Lime and Lime-Fly Ash Stabilization and published in 1976 as TRB Circular 180, the report has been revised and updated in 1986 with the committee's approval for publication.

CHAPTER 1
Soil-Lime Reactions

The addition of lime to a fine-grained soil in the presence of water initiates several reactions. Cation exchange and flocculation cause immediate improvement in soil plasticity, workability, uncured strength, and load-deformation properties. A soil-lime pozzolanic reaction may also occur to form various cementing agents that increase compacted mixture strength and durability. Pozzolanic reactions are time and temperature dependent. Ultimate cured strength development is gradual but may continue for several years in some instances. Temperatures less than 55°F to 60°F retard reaction and higher temperatures accelerate the reaction (*1*). Carbonation is the reaction of lime and atmospheric carbon dioxide to form a relatively insoluble carbonate. This detrimental chemical reaction should be avoided by properly expedited and sequenced construction procedures.

CATION EXCHANGE AND FLOCCULATION-AGGLOMERATION

Practically all fine-grained soils display rapid cation exchange and flocculation-agglomeration reactions when treated with lime in the presence of water. The lime is a source of free calcium.

Assuming equal concentrations, the general order of preferential adsorption of the common cations associated with soils is given by the lyotropic series $Na^+ < K^+ < Ca^{++} < Mg^{++}$ (*2*). Cations tend to replace cations to the left in the series and monovalent cations are usually replaceable by multivalent cations. The addition of sufficient lime creates a free Ca^{++} concentration that will replace dissimilar adsorbed cations on the colloidal surface. In some cases, the exchange complex may be Ca^{++} saturated before the lime addition, but cation exchange may still take place because the cation exchange capacity will increase as the pH increases.

Flocculation and agglomeration produce an apparent change in texture with clay particles clumping together into larger-sized aggregates. Herzog and Mitchell (*3*) state that this phenomenon is caused by the increased electrolyte concentration of the pore water and the clay surface adsorption of calcium. Diamond and Kinter (*4*) suggested that the rapid formation of calcium aluminate hydrate cementing materials are significant in the development of flocculation-agglomeration tendencies in soil-lime mixtures. Lime modification (*5*) has been used to describe this treatment phase.

SOIL-LIME POZZOLANIC REACTION

Lime, water, soil silica, and alumina react to form various cementitious compounds. Possible sources of silica and alumina in typical soils include clay minerals, quartz, feldspars, micas, and similar silicate or alumino-silicate minerals, either crystalline or amorphous in nature.

When a significant quantity of lime is added to a soil, the pH of the soil-lime mixture is elevated to approximately 12.4, the pH of saturated lime water. This is a substantial pH increase for natural soils. The solubilities of silica and alumina are greatly increased at elevated pH levels (*6*).

In an early study of soil-lime reactions, Eades (*7*) suggested that the high pH causes silica from the clay minerals to dissolve and, in combination with Ca^{++}, to form calcium silicate. This reaction will continue as long as $Ca(OH)_2$ exists in the soil and there is available silica. Diamond et al. (*8*) postulated that lime molecules are adsorbed by clay surfaces and react with other clay surfaces to precipitate reaction products.

Although these studies generally suggest a "through-solution" mechanism in which clay lattice components are "dissolved" from the clay structure and reprecipitated as CSH and CAH, direct reaction of the lime at the surface of the clay mineral particles is also plausible. The diffuse cementation theory proposed by Stocker (*9*) does not postulate lime adsorption of clay surfaces but that lime reacts directly with clay crystal edges, generating accumulations of cementitious material. Research concerning the adsorption of lime by kaolinite and montmorillonite (*10*), as well as electron optical studies of clay-lime-water systems (*11,12*), indicate that surface chemical reactions can occur and new phases may nucleate directly on the surfaces of clay particles. It is also possible that the reactions may occur by a combination of through-solution (solution-precipitation) and surface chemical (hydration-crystallization) processes.

Cabrera's work (*13*) with red tropical soils suggests that after the initial 7 days of curing, strength increases are the result of hydration and increases in crystallinity of reaction products rather than from the continued formation of additional pozzolanic compounds.

An oversimplified qualitative view of some typical soil-lime reactions is as follows:

$Ca[OH]_2 \rightarrow Ca^{++} + 2[OH]^-$
$Ca^{++} + 2[OH]^- + SiO_2$ (clay silica)$\rightarrow$CSH
$Ca^{++} + 2[OH]^- + Al_2O_3$ (clay alumina)$\rightarrow$CAH

A wide variety of hydrate forms can be obtained depending on reaction conditions (e.g., quantity and lime type, soil characteristics, curing time, and temperature). Typical soil-lime reactions are as follows:

kaolinite + lime$\rightarrow$CSH (C/S = 0.2-1.0) + CAH + CASH (*14*)
kaolinite + lime$\rightarrow$CASH (prehnite) (*15*)
montmorillonite + lime$\rightarrow$CSH (gel)$\rightarrow$CSH (II) (*16*)
montmorillonite + lime$\rightarrow$CSH (gel) + hydrogarnet (C_4AH_{13}) (*17*)
clay + lime$\rightarrow$CSH (gel) and/or CSH (I) + C_4AH_{13} + C_3AH_6 (*8*)

where C = CaO, S = SiO_2, A = Al_2O_3, and H = H_2O

Ford et al. (*12*) reported the following hydrates using cured mixtures of lime and natural clay soils of the southeastern United States: CSH (gel), CSH (I), CSH (II), C_4AH_{13}, and C_3AH_6.

Natural soil properties affect soil-lime pozzolanic reactions. The pozzolanic reaction is inhibited in some soil, and cementing agents are not extensively formed. Thompson (*18*) has termed those soils that react with lime to produce a substantial strength increase (greater than 50 psi following 28-day curing at 73°F) as reactive; those soils with lesser strength increases are called nonreactive. This terminology does not imply that lime modification does not take place.

Some of the major soil properties and characteristics that influence the lime reactivity of a soil—the ability to react with lime to produce cementitious materials—are soil pH; organic carbon content; natural drainage; presence of excessive quantities of exchangeable sodium; clay mineralogy; degree of weathering; presence of carbonates, sulfates, or both; extractable iron; silica-sesquioxide ratio; and silica-alumina ratio. Recent research by Mitchell (*19*) reiterates and clarifies the detrimental effect of sulfates that react with calcium and carbonate to form ettringite and thaumasite. These two materials are very expansive and may produce swelling characteristics that exceed those of the natural untreated soil. Furthermore, the formation of pozzolanic products is curtailed because the pH is reduced.

SUMMARY

Soil-lime reactions are complex; however, sufficient basic understanding and field experience are available to provide adequate technology for successful lime treatment of a large number of soils under a wide variety of conditions.

CHAPTER 2
Properties and Characteristics of Lime-Treated Soils

In general, all fine-grained soils exhibit improved plasticity, workability, and volume change characteristics when mixed with lime; however, not all soils exhibit improved strength, stress-strain, and fatigue characteristics. It should be emphasized that the properties of lime-soil mixtures are dependent on many variables (*18,20*). Soil type, lime type, lime percentage, and curing conditions including time, temperature, and moisture are the most important variables. More important, however, the effect produced by any given change in a given variable is dependent on the levels of the other variables.

Currently, only limited information is available concerning some of the properties of lime-treated soils. Nevertheless, in order to effectively utilize these treated soils as a structural material, it is necessary to evaluate and summarize the existing knowledge concerning the properties of soil-lime mixtures.

COMPACTION CHARACTERISTICS

The compaction characteristics, that is, maximum density and optimum moisture, are important for two basic reasons. First, an adequate level of compaction must be obtained in order to achieve satisfactory results. Second, and possibly more important, density is used for field control.

When compacted with a given effort, soil-lime mixtures have a lower maximum density than the original untreated soil, and the maximum density normally continues to decrease as the lime content is increased. In addition, the optimum moisture content increases with increasing lime content (Figure 2-1) (*21*). Similarly, if the mixture is allowed to cure so that substantial cementing occurs, the density would be further decreased and the optimum moisture increased.

Moisture-density relationships are constantly changing, and it is important that the proper curve be used in field construction. Therefore, if curing has occurred, it may be impossible to achieve density; however, it is important to realize that it is not necessary to achieve that density because the reduction is not due to poor compaction but rather to the fact that the material is different.

PLASTICITY AND WORKABILITY

Substantial reduction in plasticity, that is, reduced plasticity index (PI) and increased shrinkage limit, is produced by lime treatment, and in many cases the soil may become nonplastic. Generally, soils with a high clay content or soils exhibiting a high initial PI require greater quantities of lime for achieving the nonplastic condition, if it can be achieved at all. The first increments of lime addition are generally most effective in reducing plasticity, with subsequent additions being less beneficial (*20*). The reduced plasticity of the lime-treated soil and its silty and friable texture cause a significant improvement in workability and expedite subsequent manipulation and working of the treated soil. The manner in which lime influences the plasticity characteristics is illustrated by Figure 2-2 (22) and Table 2-1 (*20*).

VOLUME CHANGE

Swelling potential and swelling pressures normally are significantly reduced by treating clay with lime. These reduced swell characteristics are generally attributed to decreased affinity for water of the calcium-saturated clay and the formation of a

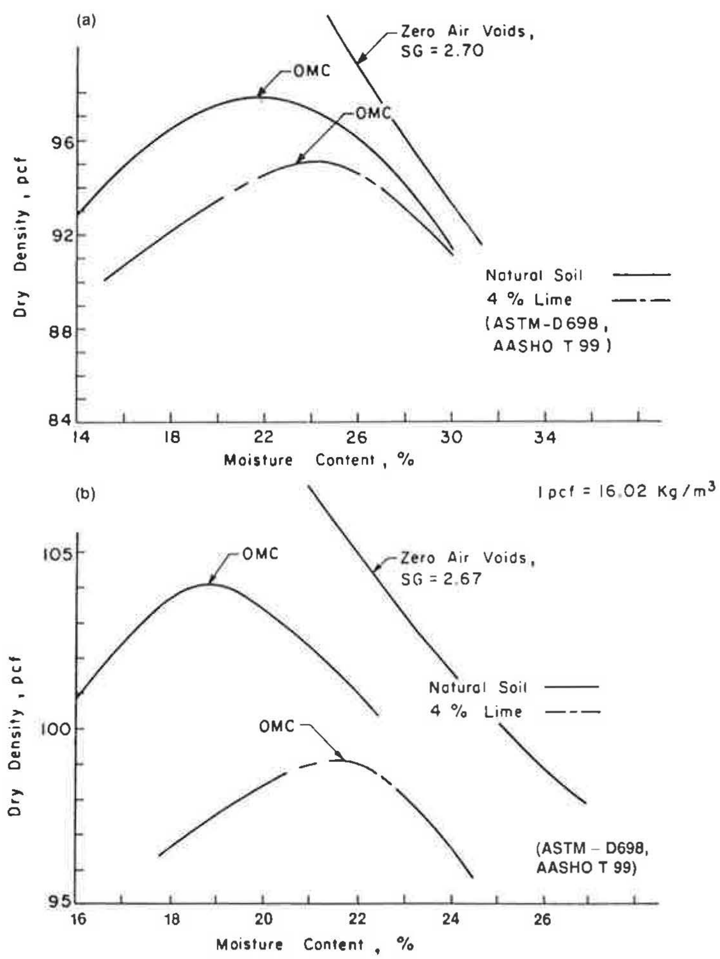

FIGURE 2-1 Typical moisture-density relationship: (a) Vicksburg buckshot clay, (b) Ava B.

TABLE 2-1 Influence of Lime on Plasticity Properties

Soil	AASHO Class	LL or PI by Percentage of Lime					
		None		3		5	
		LL	PI	LL	PI	LL	PI
Bryce B	A-7-6(18)	53	29	48	21	NP	NP
Cisne B	A-7-6(20)	59	39	NP	NP	–	–
Cowden B	A-7-6(19)	54	33	47	7	NP	NP
Drummer B	A-7-6(19)	54	31	44	10	NP	NP
Elliott B	A-7-6(18)	53	28	42	19	NP	NP
Fayette B	A-7-5(17)	50	29	NP	NP	–	–
Hosmer B_2	A-7-6(11)	41	17	NP	NP	–	–
AASHO Road Test	A-6(18)	25	11	27	6	27	5
Huey B	A-7-6(17)	46	29	40	9	NP	NP
Sable B	A-7-6(16)	51	24	NP	NP	–	–

Note: LL = liquid limit, PI = plasticity index, and NP = nonplastic.

cementitious matrix that resists volumetric expansion. California bearing ratio (CBR) swell values of lime-treated soils vary, but it is not uncommon to decrease swell to less than 0.1 percent compared to values of 7 to 8 percent for the untreated soil (Table 2-2) (*23*). Typical expansive pressures are shown in Figure 2-3 (*24*).

Shrinkage caused by moisture loss from the stabilized soil is important relative to the problem of shrinkage cracking. Lime treatment improves the shrinkage and swell characteristics of the treated materials. Data for typical Illinois soils are shown in Figure 2-4 (*25*).

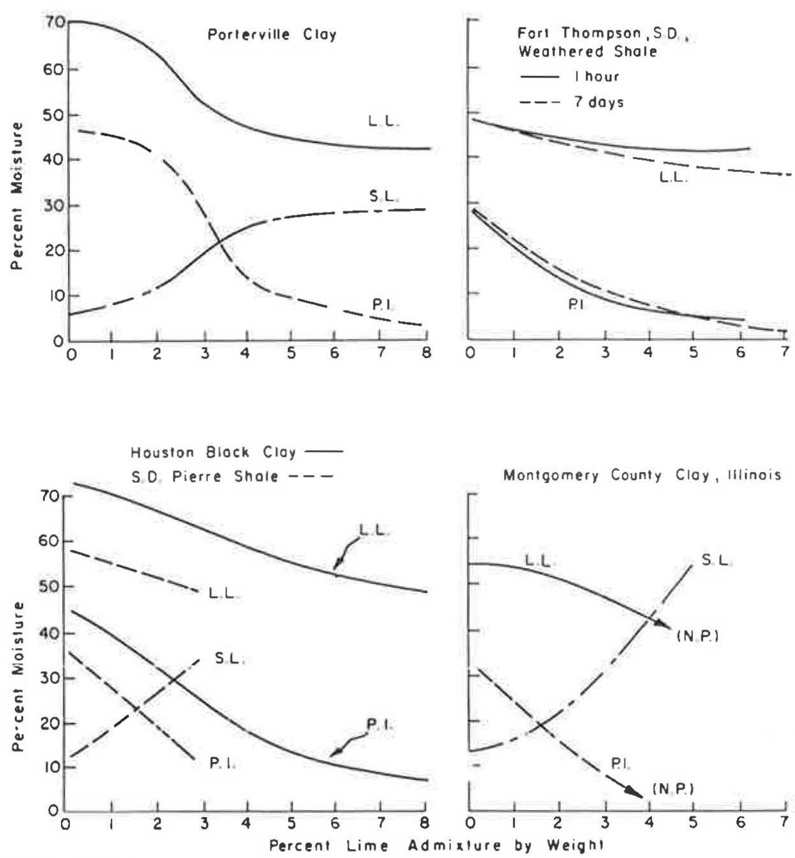

FIGURE 2-2 Effect of lime on plasticity characteristics of montmorillonite clays.

TABLE 2-2 CBR Values for Selected Soils and Soil-Lime Mixtures

Soil	Natural Soil CBR (%)	Natural Soil Swell (%)	Percentage of Lime	Soil-Lime Mixtures: No Curing[a] CBR (%)	Soil-Lime Mixtures: No Curing[a] Swell (%)	Soil-Lime Mixtures: 48-hr Curing at 120°F CBR (%)	Soil-Lime Mixtures: 48-hr Curing at 120°F Swell (%)
Good Reacting Soils							
Accretion Gley 2	2.6	2.1	5	15.1	0.1	351.0	0.0
Accretion Gley 3	3.1	1.4	5	88.1	0.0	370.0	0.1
Bryce B	1.4	5.6	3	20.3	0.2	197.0	0.0
Champaign Co. till	6.8	0.2	3	10.4	0.5	85.0	0.1
Cisne B	2.1	0.1	5	14.5	0.1	150.0	0.1
Cowden B	7.2	1.4	3	–	–	98.5	0.0
Cowden B	4.0	2.9	5	13.9	0.1	116.0	0.1
Cowden C	4.5	0.8	3	27.4	0.0	243.0	0.0
Darwin B	1.1	8.8	5	7.7	1.9	13.6	0.1
East St. Louis clay	1.3	7.4	5	5.6	2.0	17.3	0.1
Fayette C	1.3	0.0	5	32.4	0.0	295.0	0.1
Illinoian B	1.5	1.8	3	29.0	0.0	274.0	0.0
Illinoian till	11.8	0.3	3	24.2	0.1	193.0	0.0
Illinoian till	5.9	0.3	3	18.0	0.9	213.0	0.1
Sable B	1.8	4.2	3	15.9	0.2	127.0	0.0
Nonreactive Soils							
Fayette B	4.3	1.1	3	10.5	0.0	39.0	0.0
Miami B	2.9	0.8	3	12.7	0.0	14.5	0.0
Tama B	2.6	2.0	3	4.5	0.2	9.9	0.1

Note: t°F = (t°C ÷ 0.55) + 32.
[a] Specimens were placed in 96-hr soak immediately after compaction.

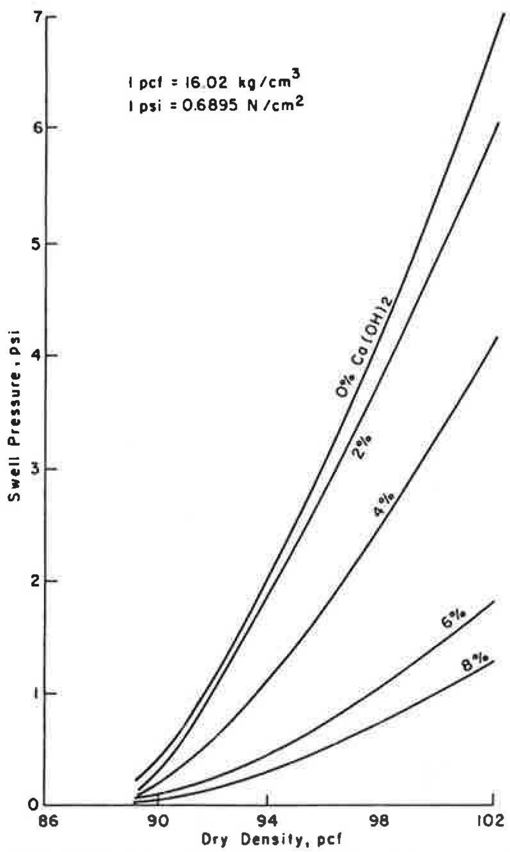

FIGURE 2-3 *Swell pressure-density relationships for lime-treated Porterville clay.*

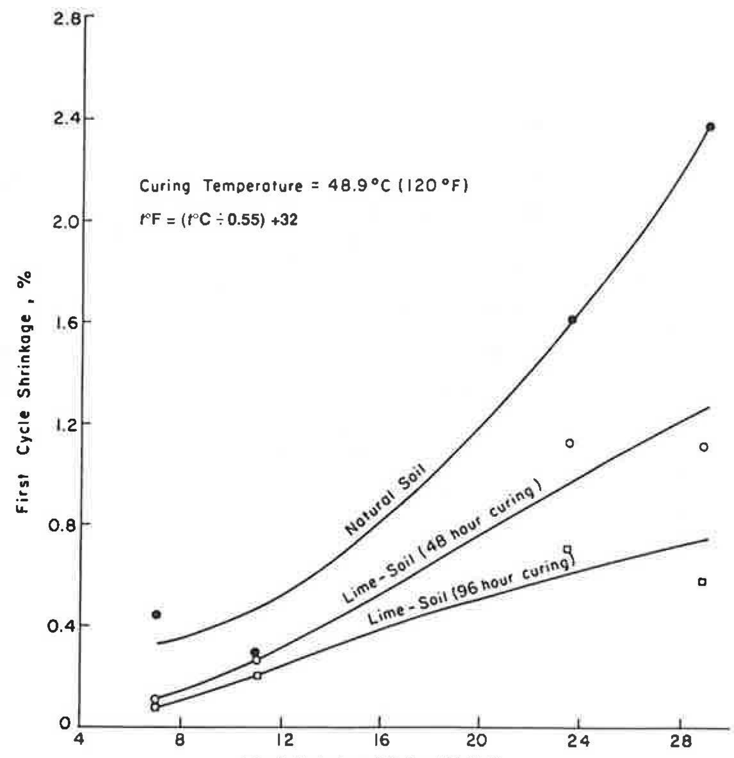

FIGURE 2-4 *Influence of PI of natural soil on first-cycle shrinkage.*

Field moisture contents of lime-treated soils suggest that the moisture-content changes in the stabilized material are not large and the in-situ water content stabilizes at approximately optimum (*26*). Theoretical calculations based on laboratory shrinkage data, as well as field-service data from many areas, indicate that for typical field conditions shrinkage will not be extensive (*26*).

STRENGTH

The strength of lime-soil mixtures can be evaluated in many ways. The unconfined compression test is the most popular procedure, and the stabilometer and CBR tests are used to a lesser extent. These methods, however, are definitely not the most applicable or desirable. Only limited data are available concerning the tensile properties of lime-soil mixtures (*27–30*), and additional effort is needed to evaluate the tensile characteristics of lime-treated materials.

It should be emphasized that the strength of a soil-lime mixture is dependent on many variables and that it varies substantially (*18,20*). Soil type, lime type, lime percentage, curing conditions of time and temperature, and the interactions between these variables are the major factors influencing strength (*27,28,30*).

A distinction must be made with respect to curing. An immediate beneficial strength effect occurs with the addition of lime as a result of the immediate reactions (cation exchange, flocculation, and agglomeration). The long-term strength gain is primarily related to the pozzolanic reaction. Therefore, it is necessary to divide the discussion between cured and uncured strength.

Uncured Strength

Immediately after the addition of lime a substantial improvement in strength and stability can be expected (*21,31*). These immediate effects can be considered to be an expedient of construction when soft, highly plastic, cohesive soils create mobility problems for wheeled vehicles (Figure 2-5 to 2-7) or do not provide satisfactory subgrade support for pavement construction operations.

FIGURE 2-5 Partially completed stabilized subgrade resists rutting during rain at Dallas–Fort Worth Airport.

FIGURE 2-6 Comparison of ruts in untreated and lime-treated subgrade.

Examples of the immediate effect of lime treatment on cone index, CBR, and unconfined compressive strength are shown in Figure 2-8 (*21*), which shows that substantial improvements in strength can be realized. In some cases these increases may amount to several 100 percent.

Cured Strength

Unconfined Compression

Unconfined compressive strengths of typical fine-grained soils compacted at optimum moisture content and density (ASTM D2166) range from about 25 psi (17 N/cm^2) to more than 300 psi (207 N/cm^2) depending on the nature of the soil. Soil-lime mixture strength increases for Illinois soils cured 28 days at 22.8°C (73°F) with a range up to approximately 265 psi (183 N/cm^2); many soils display increases greater than 100 psi (70 N/cm^2). Extended curing of 56 days at 22.8°C (73°F) of the same mixtures produced strength increases for some soil-lime combinations that exceeded 625 psi (430 N/cm^2). Prolonged curing for 75 days at 48.9°C (120°F) of the AASHTO Road Test embankment soil treated with 5 percent lime produced an average compressive strength of 1,580 psi (1090 N/cm^2). Field data indicate that with some soil-lime mixtures, strength continues to increase with time up to and in excess of 10 years. Typical results for various densities are shown in Figure 2-9 (*23*).

The difference between the compressive strengths of the natural and lime-treated soil has been used as an indication of the degree to which the soil-lime pozzolanic reaction has proceeded (*18*). Substantial strength increase indicates that the soil is reactive with lime and can probably be stabilized to produce a quality paving material.

Shear Strength

Unconsolidated and undrained types of triaxial testing have been utilized to partially simulate field service conditions. The major effect of lime on the shear strength of a reactive fine-grained soil is to produce a substantial increase in cohesion with some minor increase in the angle of internal friction. At the low confining pressures normally considered to exist in a flexible pavement structure, the cohesion increase is of the greatest significance. For materials such as soil-lime mixtures characterized by very high cohesion, it is difficult to effectively evaluate the angle of internal friction.

For the typical lime-reactive Illinois soils, the angle of internal friction for soil-lime mixtures ranged from 25 to 35 degrees (*32*). The cohesion of the mixtures was substantially increased compared to the natural soils and cohesion continued to

FIGURE 2-7 Excellent condition of lime-stabilized clay lining of Friant Kern Canal, California, noted during dewatering 12 years after completion of project.

increase with increased unconfined compressive strength. Using the linear regression equation shown in Figure 2-10 (32), cohesion values can be estimated from unconfined compressive strength results.

It is apparent that large shear strengths can easily be developed in cured soil-lime mixtures. It has been demonstrated that if high-quality mixtures are used in typical flexible pavement structures, the strengths would be adequate to prevent shear failure (32). Shear-type failures generally have not been observed and reported for field service conditions.

Tensile Strength

Tensile strength properties of soil-lime mixtures are of concern in pavement design because of the slab action that is afforded by a material possessing substantial tensile strength. Two test procedures, indirect tensile and flexural, have been used for evaluating the tensile strength of soil-lime mixtures.

The indirect tensile test is essentially a diametral compression test in which the material fails in tension along the loaded diameter of the cylindrical test specimen.

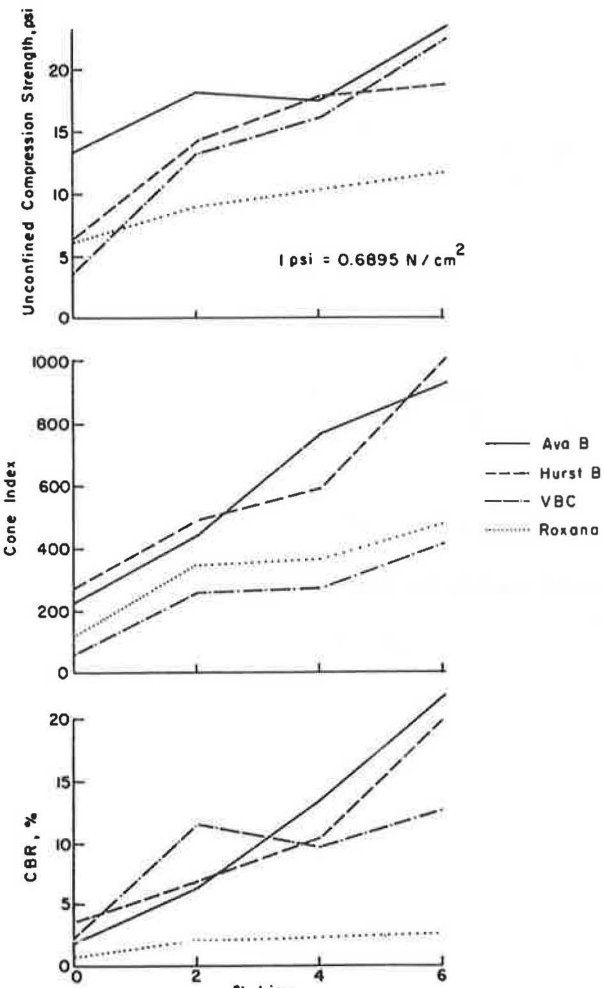

FIGURE 2-8 Immediate effects of lime treatment on strength.

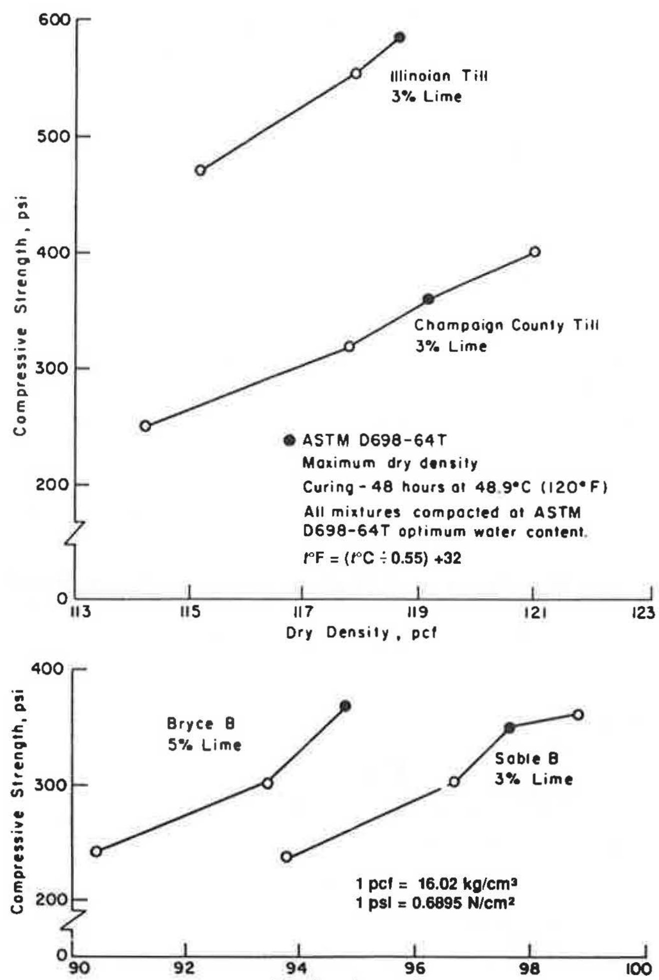

FIGURE 2-9 Influence of density on the strength of cured soil-lime mixtures.

Details and an evaluation of the test procedure for soil-lime mixtures are given elsewhere (*27–30*).

Typical results (Figure 2-11) (*29*) indicate that the mixtures can possess substantial tensile strength. The ratio of indirect tensile strength to unconfined compressive strength in one study (*29*) was found to be approximately 0.13, while in another study (*30*) it was found to be much lower as indicated by the following regression equation:

$$S_T = 6.89 + 50.6q_u$$

where S_T is the tensile strength in pounds per square inch and q_u is the unconfined compressive strength in kips per square inch.

The most common method used for evaluating the tensile strength of highway materials has been the flexural test. Typical flexural strengths of soil-lime mixtures (*33*) subjected to various curing conditions are given in Table 2-3 (*23*). Indirect tensile strengths are given for comparison purposes. For a specific mixture, the ratio of the flexural strength to indirect tensile strength decreases as strength increases and the ratio is apparently not the same for all soil-lime mixtures.

If the ratio of flexural strength to indirect tensile strength is taken as approximately 2, a realistic estimate of flexural strength is 25 percent of the unconfined strength. The ratio is approximately equivalent to those reported for lime-flyash-aggregate and soil-cement mixtures.

California Bearing Ratio

The CBR testing procedures have been extensively used to evaluate the strength of lime stabilized soils. Many agencies have arbitrarily adopted this technique because of their familiarity with the test. In reality, however, the CBR test is not appropriate for characterizing the strength of cured soil-lime mixtures. Extensive CBR tests have been conducted (*23*) with various representative Illinois soils, including soils that reacted well with lime, and also less reactive fine-grained soils.

Lime-treated soils were cured for 48 hr at 48.9°C (120°F) and companion specimens that had not been cured were placed in the 96-hr soaking cycle immediately after compaction. The 48-hr curing period is approximately equivalent to 30 days at 21.1°C

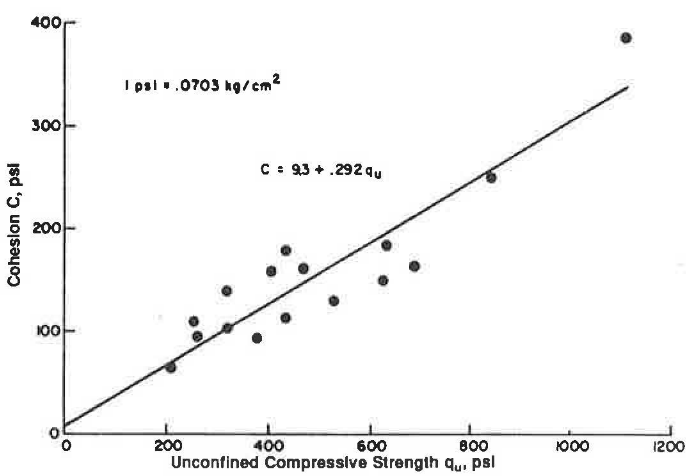

FIGURE 2-10 Cohesion versus unconfined compressive strength of soil-lime mixtures.

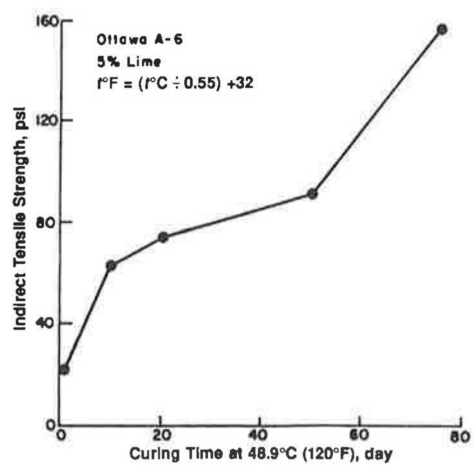

FIGURE 2-11 Indirect tensile strength of a cured soil-lime mixture.

TABLE 2-3 Tensile Strength Properties of Soil-Lime Mixtures

Soil	Percentage of Lime	Curing Time[a] (hr)	Flexural Strength σ_F (psi)	Indirect Tensile Strength σ_T (psi)	σ_F/σ_T
Bryce B	5	24	92	42	2.2
		48	105	53	2.0
		96	122	88	1.4
Champaign County	3	48	69	–	–
till[b]		96	93	–	–
Fayette C	5	24	66	46	1.4
		96	166	126	1.3
Illinoian till,	3	24	86	35	2.5
Sangamon County		48	164	92	1.8
		96	202	106	1.9
Sable B[b]	3	48	63	–	–
		96	77	–	–
Wisconsin loam till	3	24	83	35	2.4
		48	140	63	2.2
		96	157	78	2.0

Note: 1 psi = 0.6895 N/cm^2; t°F = (t°C ÷ 0.55) + 32.
[a] At 120°F.
[b] Test not conducted for indirect tensile strength σ_T.

(70°F), and the mixtures that were not cured before soaking had little opportunity to develop cementitious products from the soil-lime pozzolanic reaction. The improvements in engineering properties of the uncured soil-lime mixtures were therefore primarily a result of the cation exchange, flocculation, and agglomeration produced by the addition of lime. Test results for the natural soils and the soil-lime mixtures are given in Table 2-2. The CBR increases of the uncured soil-lime mixtures show the benefits that can be obtained from stabilization without prolonged curing. It is apparent that the uncured specimens have not developed extensive cementing action.

The CBR values for many of the soil-lime mixtures cured for 48 hr at 48.9°C (120°F) are quite large and definitely indicate the extensive development of cementing agents. For those mixtures that display CBR values of 100 or more, the test results have little practical significance and are not meaningful as a measure of strength or stability. In general, these materials would also exhibit high compressive and tensile strengths, and these types of tests would provide a better strength evaluation. If extensive cementing action has not developed as a result of either lack of curing time or nonreactivity of the treated soil, CBR values may serve as a general measure of strength; but even in these cases the use of the CBR test is questionable. It is evident that lime treatment of fine-grained soils produces increased CBR irrespective of the length of curing and lime-reactivity of the soil.

STRESS-STRAIN CHARACTERISTICS

Stress-strain properties are essential for properly analyzing the behavioral characteristics of a pavement structure containing a soil-lime mixture structural layer. The marked effect of lime on the compressive stress-strain properties of fine-grained soils is shown in Figure 2-12 (32). The failure stress is increased, and the ultimate strain is decreased for soil-lime mixtures relative to the natural soil. As with strength, it is necessary to separate the discussion with regard to whether the soil-lime has been cured or not because immediate beneficial effects occur that relate to improved workability and construction.

Uncured Soil-Lime

Typical improved stress-strain characteristics that occur without curing are shown in Figure 2-13 (*21*), and the general nature of the modification attained from lime treatment is indicated. Substantial increases in modulus of deformation can be expected.

Typical stress strain relationships for soil and soil-lime compacted on the wet side of optimum to simulate a wet field condition during construction are shown in Figure 2-14 (*34*).

Cured Soil-Lime

As a result of an extensive study of representative Illinois soils stabilized with lime (32), it was possible to develop a generalized compressive stress-strain relation for cured soil-lime mixtures (Figure 2-15). The mixtures studied appeared to be strain susceptible, and the ultimate strain at maximum compressive stress was approximately 1 percent, regardless of the soil type or curing period.

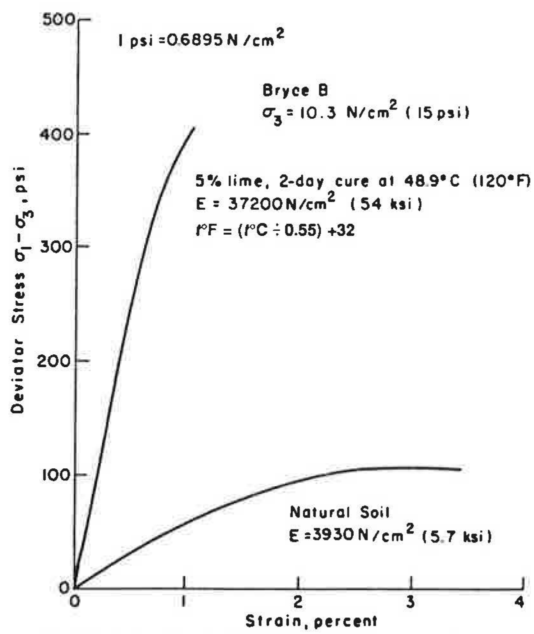

FIGURE 2-12 Typical stress-strain curves for natural and lime-treated soil.

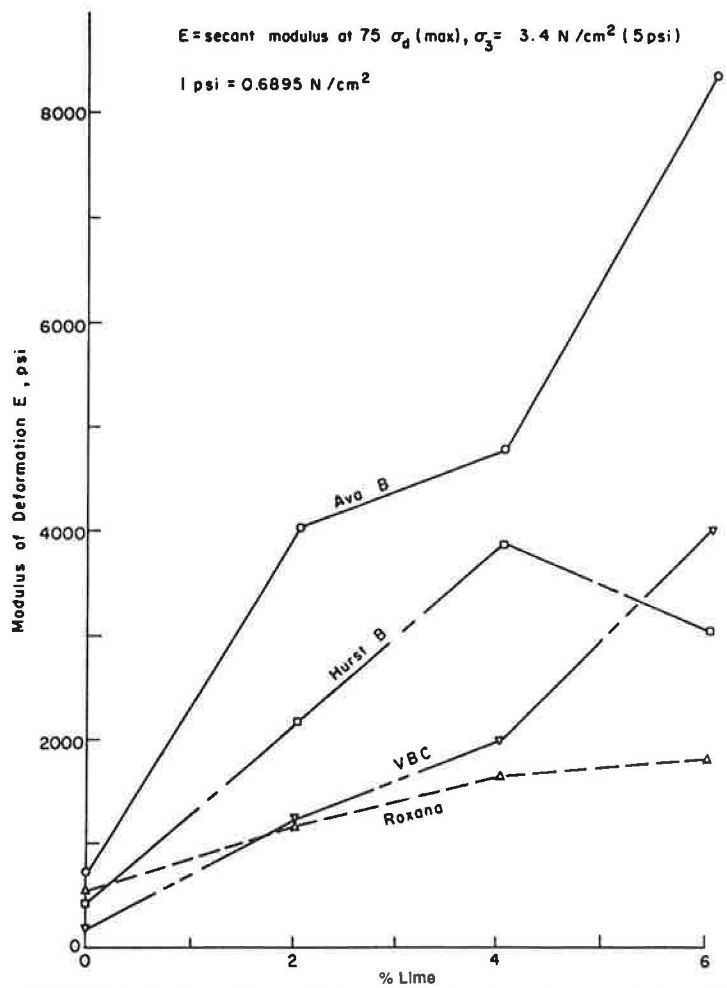

FIGURE 2-13 Immediate effects of lime treatment on modulus of deformation.

Modulus of Deformation or Elasticity

It was found (*32*) that the compressive modulus of elasticity at a confining pressure of 15 psi (1.05 kg/cm²) could be estimated from the unconfined compressive strength of the lime-soil mixture according to the following relation:

$$E = 9.98 + 0.124q_u$$

where E is the compressive modulus of elasticity in kips per square inch and q_u is the unconfined compressive strength in pounds per square inch.

For soil-lime pavement layers possessing high shear strength, the flexural stresses in the mixture may be the controlling design factor. In view of this fact, flexural moduli of elasticity have been evaluated for typical cured soil-lime (*32*).

Typical Illinois soils were stabilized with lime, and beams with dimensions of 2 × 2 × 9 in. (5.08 × 5.08 × 22.86 cm) were prepared and cured for 48 and 96 hr at 48.9°C (120°F). After curing, strain gauges were attached to the middle portion of the beams and the beams were tested under third-point loading conditions.

The modulus of elasticity in flexure was calculated from the moment-curvature relationships for the beams, and the relationship between the modulus of elasticity and the flexural strength was calculated (Figure 2-16) (*23*). For the range of data considered, it was concluded that the regression equation shown in Figure 2-16 can be used to estimate the flexural modulus of elasticity. It should be noted that flexural moduli were substantially larger than compressive moduli for the same mixture.

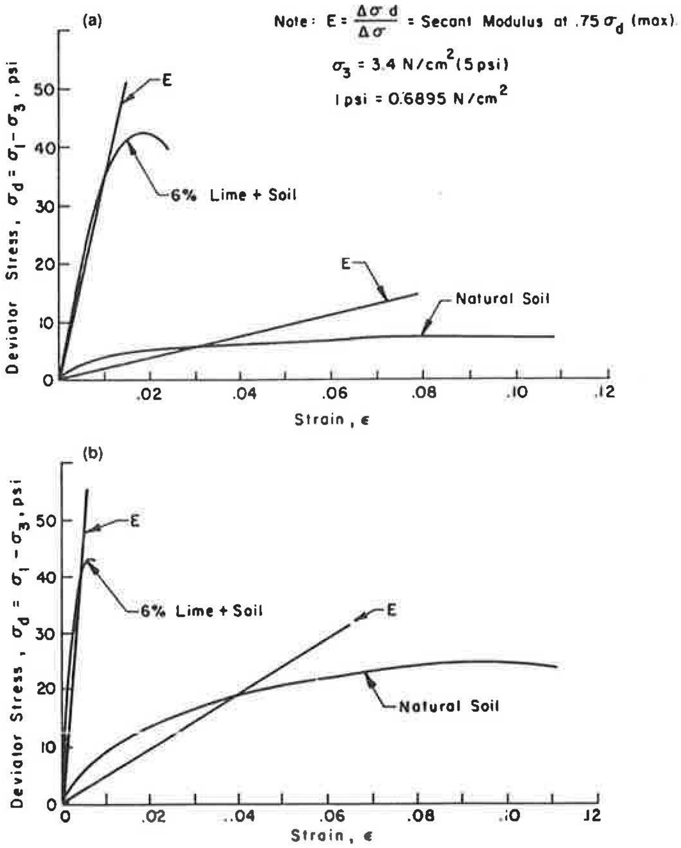

FIGURE 2-14 Typical stress-strain curve showing immediate effects of lime treatment: (a) Vicksburg buckshot clay, (b) Ava B.

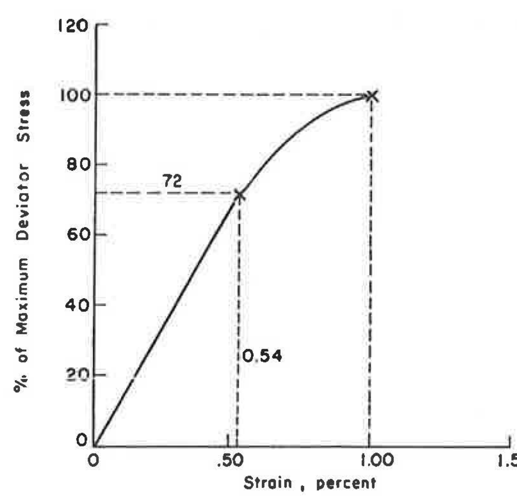

FIGURE 2-15 Generalized stress-strain relationship for cured soil-lime mixtures.

Repeated compressive loading data for soil-lime mixtures are limited. Using a montmorillonitic clay treated with 10 percent lime, Fossberg (*35*) studied the influence of deviator stress and confining pressure on resilient modulus. The specimens were prepared at extremely high water contents and low densities. Consequently the data are not directly comparable with field conditions. The general relation between resilient modulus and principal stress ratio appeared to be linear and resilient moduli in excess of 100,000 psi (69 000 N/cm²), as noted for some test conditions, even under the rather unfavorable testing conditions involving high water content and low density.

Maxwell and Joseph (*36*) used a field vibratory testing procedure for evaluating the strength of an airfield pavement section containing a 6-in. (15.2-cm) lime-stabilized subgrade and an 8-in. (20.3-cm) lime-stabilized clay-gravel subbase. Based on periodic field-velocity measurements, computed elastic moduli for the stabilized subgrade ranged from 165,000 psi (114 000 N/cm²) following construction to 568,000 psi (392 000 N/cm²) approximately 2–2.5 years after construction. Similar data for the lime-treated subbase were 196,000 psi (135 000 N/cm²) after construction and 1,010,000 psi (696 000 N/cm²) 2–2.5 years later.

Poisson's Ratio

Only limited data are available for lime-soil mixtures. Reported values at stress levels less than 25 percent of ultimate compressive strength ranged from 0.08 to 0.12 with an average of 0.11 (*23*). These values are in agreement with those previously reported for rock, lime-flyash-aggregate mixtures, and soil cement. At higher stress levels, greater than 50 to 75 percent of ultimate compressive strength, Poisson's ratio increased, ranging from 0.27 to 0.37 with an average of 0.31. A similar type of behavior has been noted for lime-flyash-aggregate mixtures. The influence of stress level, expressed as a percent of ultimate compressive strength, on Poisson's ratio for soil-lime mixtures is shown in Figure 2-17 (*23*).

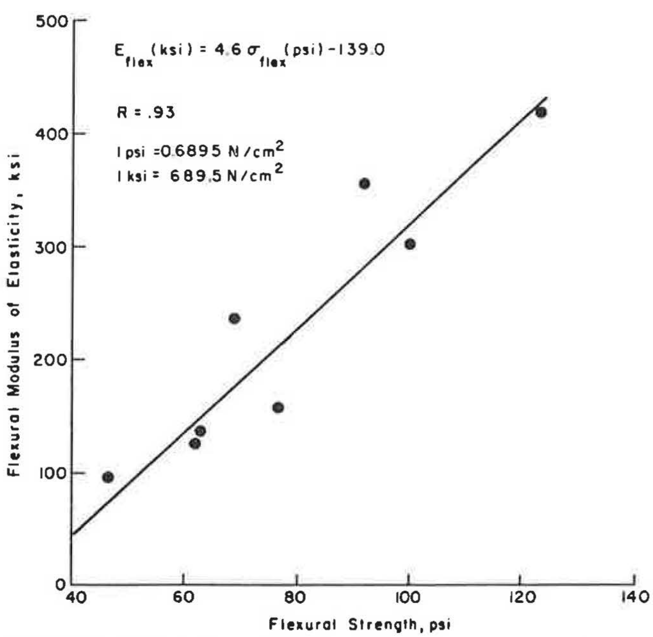

FIGURE 2-16 Relationship between flexural strength and flexural modulus for soil-lime mixtures.

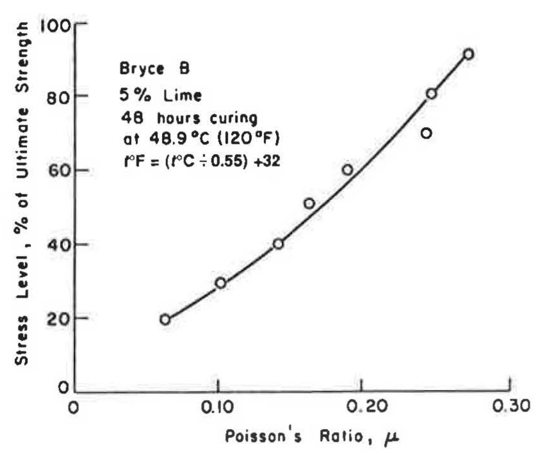

FIGURE 2-17 Influence of stress level on Poisson's ratio.

General

Because the properties of a soil-lime mixture change with increased curing time, it may not be justified to conduct elaborate tests to precisely evaluate properties that will change as a result of field curing effects. It may be more desirable to use unconfined compressive strength or the indirect tensile test for evaluating the quality of the mixtures. Use of correlations instead of testing is discouraged because these correlations depend on the conditions for which they were developed and can produce large errors. Correlations should be used only when there is no other alternative or when the desired property cannot be measured, and then used only with caution.

FATIGUE CHARACTERISTICS

The flexural strength of soil-lime mixtures is important to use in subbase and base courses. Flexural fatigue data developed for typical Illinois soils are shown in Figure 2-18 (*33*).

The response curves are typical of fatigue in general and are similar to the curves normally obtained for similar materials such as lime-flyash-aggregate mixtures and concrete. The fatigue strengths at 5 million stress repetitions of the lime-soil mixtures varied from 41 to 66 percent of the ultimate flexural strength with an average of 54 percent.

More important is the behavior of lime-treated mixtures when subjected to repeated applications of tensile stresses such as in the indirect tensile test or the direct tensile

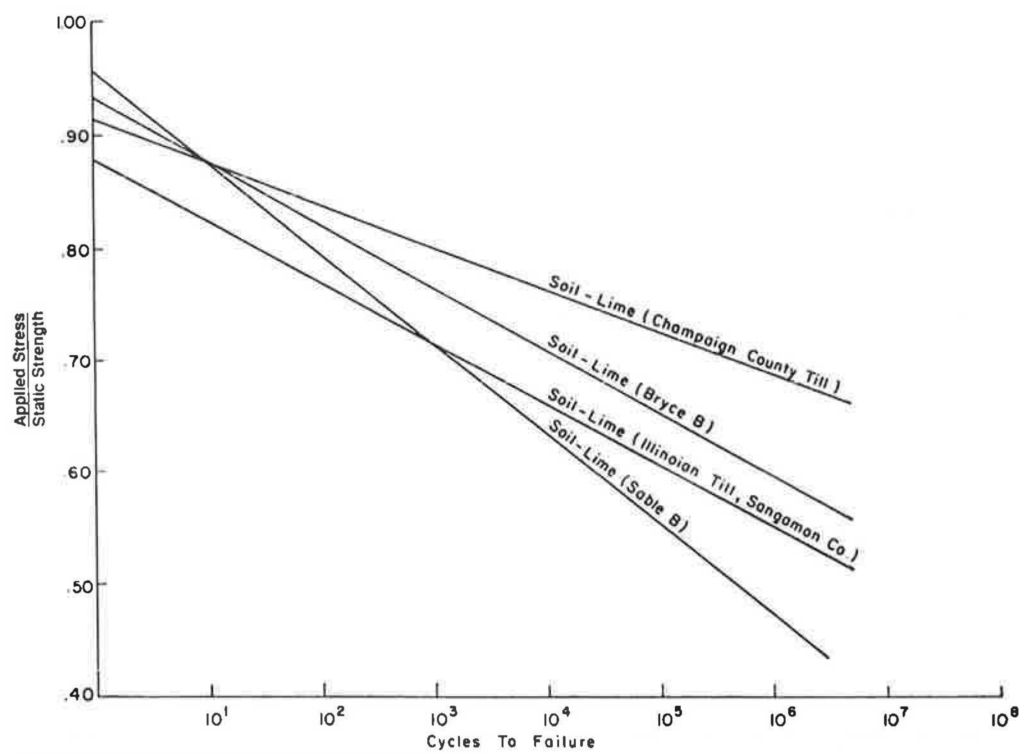

FIGURE 2-18 Flexural fatigue response curves.

test. Fatigue experiments using the indirect tensile test indicated that this test is quite applicable to the study of lime-treated materials (*37*).

Soil-lime mixtures continue to gain strength with time, and the ultimate strength of the mixture is a function of curing period and temperature. The magnitudes of the stress repetitions applied to the mixture are relatively constant throughout its design life. Therefore, as the ultimate strength of the material increases due to curing, the stress level, as a percent of ultimate strength, will decrease and the fatigue life of the mixture will increase.

DURABILITY

The major durability consideration for soil-lime mixtures is the resistance to cyclic freezing and thawing. Prolonged exposure to water produces only slight detrimental effects and the ratio of soaked to unsoaked compressive strength is high at approximately 0.7 to 0.85 (*26*). The general relation between soaked and unsoaked strengths for typical lime stabilized Illinois soils is shown in Figure 2-19 (*26*). The soaked specimens seldom achieved 100 percent saturation, and in most cases the degree of saturation was in the range of 90 to 95 percent. Similar response to soaking has been noted in extensive studies conducted by the Transport and Road Research Laboratory, United Kingdom (*38*).

In zones where freezing temperatures occur, freeze-thaw damage may result. The damage is generally characterized by volume increase and strength reduction as shown in Figures 2-20 and 2-21 (*39*). The interrelation between length changes and compressive strength decreases is shown in Figure 2-22. The validity of using initial unconfined compressive strength as a measure of freeze-thaw resistance is demonstrated in Figure 2-23 (*39*). Average rates of strength decrease for the typical mixtures

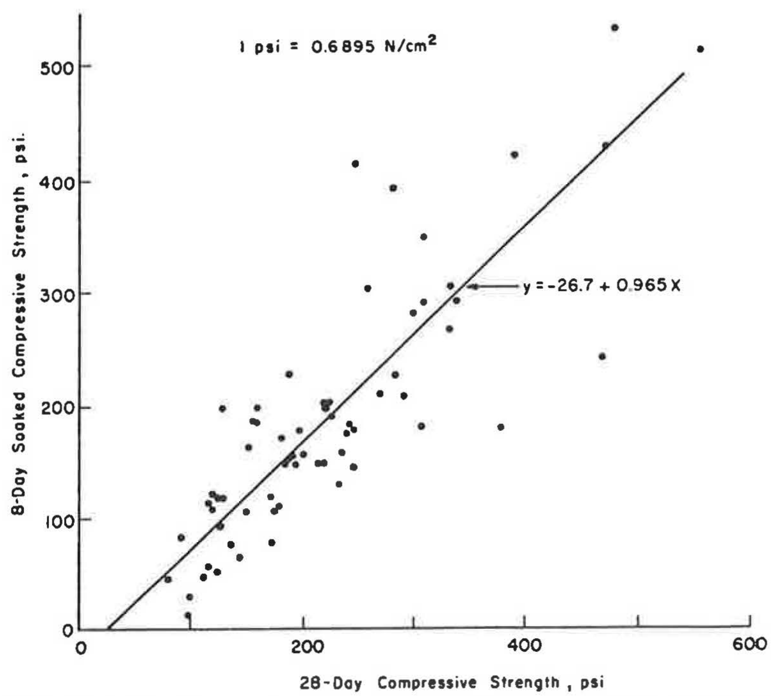

FIGURE 2-19 Influence of soaking on the strength of cured soil-lime mixtures.

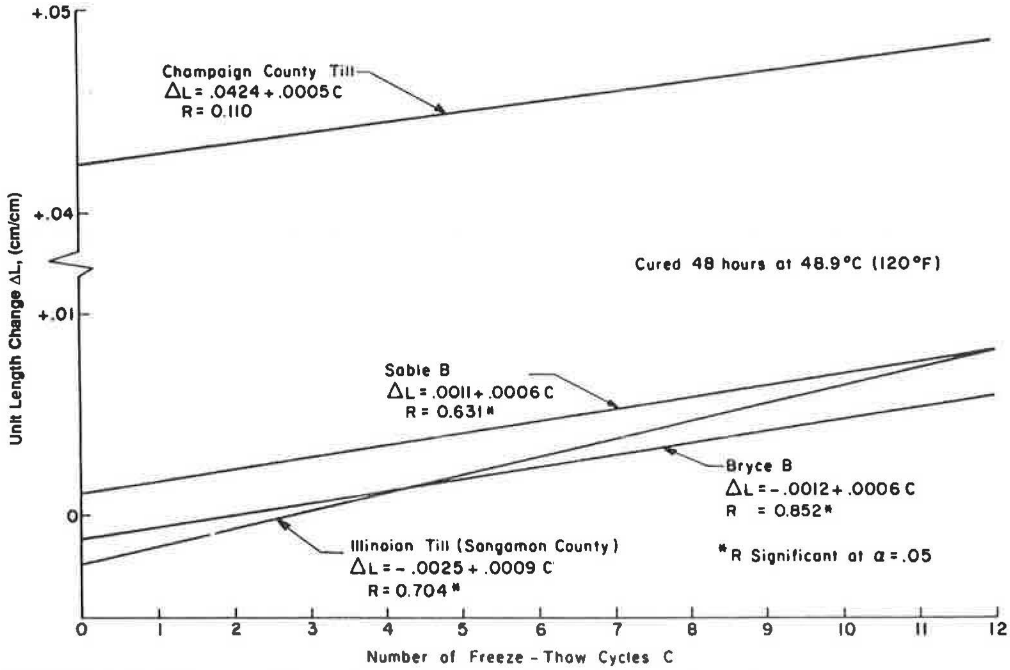

FIGURE 2-20 Influence of freeze-thaw cycles on unit length change for 48-hr curing.

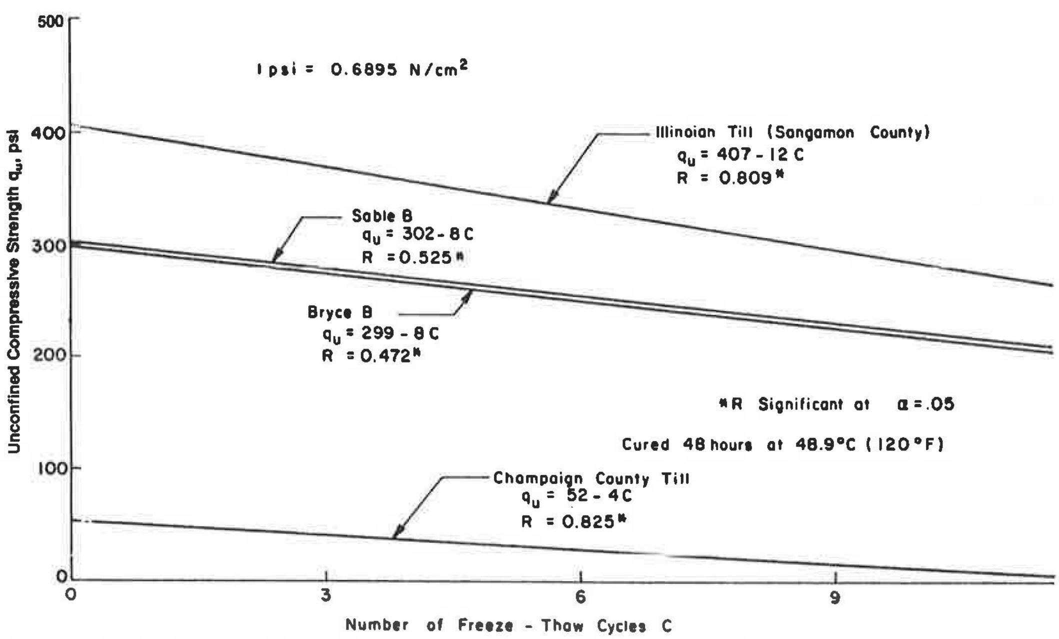

FIGURE 2-21 Influence of freeze-thaw cycles on unconfined compressive strength.

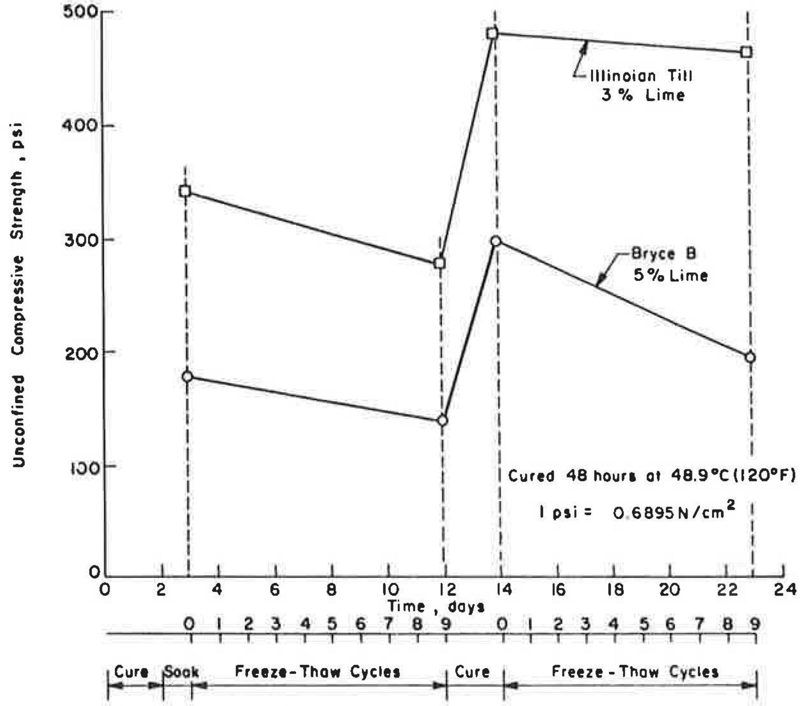

FIGURE 2-24 Influence of cyclic freeze-thaw and intermediate curing on unconfined compressive strength.

were 9 psi per cycle (6.21 N/cm² per cycle) and 18 psi per cycle (12.4 N/cm² per cycle) for 48- and 96-hr curing at 48.9°C (120°F), respectively (*39*).

A study (*40*) has shown that some soil-lime mixtures display autogenous healing properties. If the stabilized soil has the ability to regain strength or heal with time, the distress produced during winter freeze-thaw cycles will not be cumulative because autogenous healing during favorable curing conditions would serve to restore the stability of the material. This phenomenon is illustrated in Figure 2-24 (*40*). Confirming field data on autogenous healing have been presented by McDonald (*41*).

Durable soil-lime mixtures can be obtained when reactive soils are stabilized with lime. Although some strength reduction and volume change may occur, the residual strength of the stabilized materials is adequate to meet field service requirements. Durability considerations must be taken into account in establishing the mix design and selecting design strength parameters.

A classic example of the durability of lime-stabilized soil is the Friant-Kern Canal in California shown in Figure 2-7. The excellent condition of the stabilized banks after 12 years of service under water is shown (*42–44*).

VARIABILITY OF PROPERTIES

Analyses of testing error associated with repeat strength determinations of identical soil-lime mixture specimens have been reported by Liu and Thompson (*45*). The standard deviations for unconfined compression, indirect (split) tensile, and flexural strengths increased with increased strength and the average coefficients of variation. In general, the testing errors were approximately of the same magnitude, and

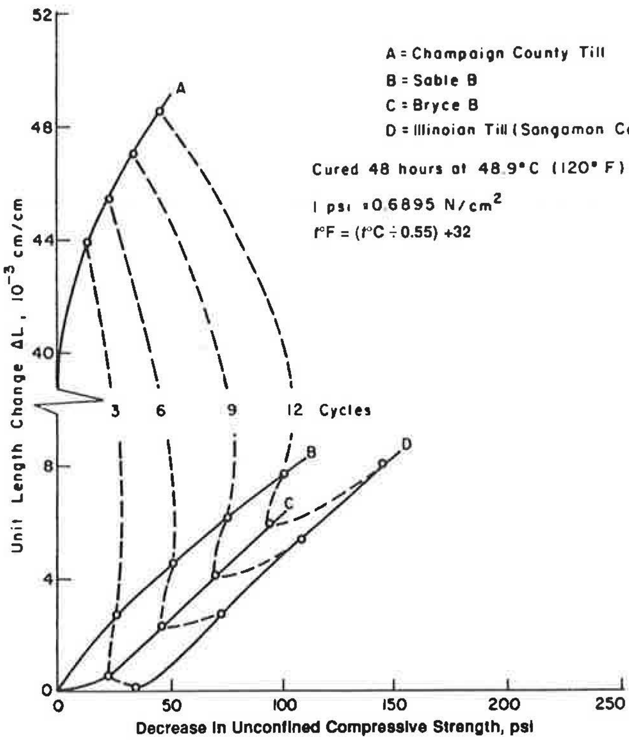

FIGURE 2-22 *Relationship between unit length change and strength decrease with freeze-thaw cycles.*

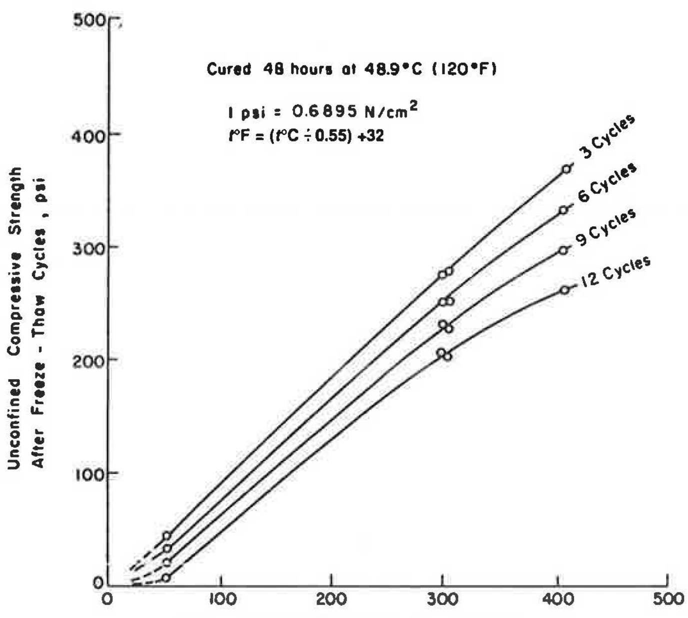

FIGURE 2-23 *Influence of initial unconfined compressive strength on the residual strength after freeze-thaw cycles.*

coefficients were of variation of 11 to 12 percent for the different testing procedures studied. This variation was for specimens prepared, cured, and tested in the laboratory. The variation for soil-lime mixtures constructed in the field would be substantially greater (*46*).

Factors contributing to testing variability include (a) heterogenous nature of soils, (b) nonuniformity of mixtures, (c) slight deviations in sample preparation and testing techniques, (d) small variations in curing temperature and time, and (e) density variations.

Moving from the laboratory to a field construction site, it could be expected that more variation would be introduced as a result of the relatively uncontrolled construction process as compared to the carefully controlled laboratory conditions. Additional variation may also be introduced with time during construction. The variation in material properties introduced along the roadway includes variation introduced by the environment, changes in the constituents of the mixture, changes in contractor or construction technique, and various other factors. This variability should be recognized and considered in the evaluation of soil-lime mixtures.

SUMMARY

An attempt has been made to summarize the basic characteristics and properties of soil-lime mixtures with respect to their engineering uses. These properties vary significantly depending on the type of soil, method and quality of construction, and type and length of curing. Thus, at this time it is not possible to define the actual properties; only values can be provided. The use, evaluation, and mixture design procedures should be developed in terms of intended use, objectives, and test conditions. In addition, the evaluation should be based on meaningful tests that provide fundamental engineering properties rather than empirical test results. An attempt should also be made to recognize and consider the inherent variation in soil-lime mixtures.

CHAPTER 3
Soil-Lime Mixture Design

The major objective of the mixture design process is to establish an appropriate lime content for construction. It is important to note that the lime percentage is the primary variable that can be altered because the inherent properties and characteristics of the soil are essentially fixed. Because of the many varied applications of lime treatment of soils, several mixture design procedures have been developed and are described in this section. The general principle of soil-lime mixture design is that the mixture should provide satisfactory performance when constructed in a desired position in the pavement structure or the subgrade. It is apparent that a wide range of soil-lime mixtures of varying quality can be successfully used to accomplish differing lime treatment objectives. Design lime contents are generally based on an analysis of the effect of various lime percentages on selected engineering properties of the soil-lime mixture. Depending on the stabilization objectives, engineering properties that are considered include Atterberg limits (liquid limit, plastic limit, and PI); swell potential, and strength of cured or uncured mixtures.

Mixture design criteria are needed to establish the quantity of lime required to produce an acceptable quality mixture. For some stabilization objectives and soils, acceptable soil-lime mixtures may not be produced regardless of the lime percentage used.

LABORATORY TESTING PROCEDURES

Many different laboratory testing procedures have been utilized in the various mixture design methods. Specific details of the various procedures have not been included in this report; however, general considerations are summarized in the following subsections.

Test methods that have been used in the design of soil-lime mixture include (a) Atterberg limits, (b) CBR, (c) Hveem stabiliometer or R-value, (d) swell tests, and (e) unconfined compression. Laboratory testing involves soil-lime mixture preparation, specimen preparation, curing, and testing.

Mixture Preparation

Lime contents are generally specified as a percentage of the dry weight of soil, although a few agencies specify a volume basis. Soil-lime mixtures are normally

prepared first by dry mixing the proper amounts of soil and lime and then by blending the required amount of water into the mixture. In most procedures, mixtures are prepared at or near optimum moisture content as determined by AASHTO T–99, T–180, or T–212.

Frequently, the soil-lime mixture is allowed to mellow 1 hr or some other designated time before conducting Atterberg limit tests or preparing test specimens.

Specimen Preparation

Strength-test specimens are generally cylindrically shaped. Diameter and heights vary substantially ranging from 1.4 in. (35.6 mm) in diameter by 2.8 in. (71.1 mm) high to 6 in. (15.2 cm) in diameter by 8 in. (20.3 cm) in height. Because the length-to-diameter (*l*/*d*) ratios vary, it is recommended that compressive strength values be corrected to an *l*/*d* ratio of 2 for comparison purposes.

The density of the compacted specimens must be carefully controlled because the strength of a cured soil-lime mixture is greatly influenced by density (Figure 2-8) and small density variations may make it difficult to accurately evaluate the effect of other variables such as lime percentage and curing conditions. Thus, the compactive effort should always be specified because some test methods specify AASHTO T–99 or the equivalent, and other procedures specify AASHTO T–180 or T–212.

Curing Conditions

Time, temperature, and moisture conditions during the curing period vary significantly. Some agencies cure at room temperatures while others cure at elevated temperatures [48 hr at 48.9°C (120°F)]. Normally, elevated temperature curing is of shorter duration than ambient curing. Many procedures specify that the specimens should be cured in a sealed container while others (AASHTO T–220) require a moist curing cycle followed by a drying and capillary wetting cycle. It should be noted that in some procedures no curing period is required.

The great disparity in curing conditions makes it very difficult to compare the results obtained from different testing methods. Thus, mixture quality criteria developed for a particular test procedure should not be arbitrarily adopted for analyzing test results obtained from a different test method.

Testing

Procedures used to evaluate soil-lime specimens usually involve conventional tests. For example, the Atterberg limits (AASHTO T–89, T–90); CBR (AASHTO T–193); and R-value (ASTM D2844) are used for many different types of materials. There is probably more variation in unconfined compression testing than any other procedure. Thus, details concerning specimen size, rate of loading, and so on, should be specified in the description of any test method that is not standardized.

MIXTURE DESIGN CRITERIA

Mixture design criteria are needed to evaluate the adequacy of a given soil-lime mixture. Criteria will vary depending on the stabilization objectives and anticipated field service conditions, such as environmental factors, wheel loading considerations, and design life. Therefore, it is apparent that mixture design criteria may range over a broad scale and should be based on a careful consideration of the specific conditions associated with the stabilization project.

Types of Criteria

Current mixture design criteria can be classified into two broad categories. The first relates to situations where the major stabilization objectives are PI reduction, improved workability, immediate strength increase, and reduced swell potential. To a large extent, these property improvements are produced by the cation exchange and flocculation-agglomeration reactions that occur quite rapidly. Mixture design criteria for this category of stabilization might typically include some of the following requirements:

1. No further decrease in PI with increased percentage of lime,
2. Acceptable PI reduction for the particular stabilization objective,
3. Acceptible swell potential reduction, and
4. CBR and R-value increase sufficient for anticipated uses.

It is difficult to establish actual quantitative values for the above requirements because in many cases they must be established relative to the properties of the untreated soil and the specific job conditions.

The second category of criteria concerns strength improvement produced by the pozzolanic reaction between the soil and lime. For example, if the mixture is to be used as a subbase or base course in the pavement structure, it must possess minimum strength and durability. Thus, mixture design criteria normally specify that the cured mixture meet a minimum strength requirement and the design lime content is the percentage that produces maximum strength for given curing conditions.

Most current minimum strength criteria are specified in terms of compressive strength. The minimum strength requirements are generally higher for base materials than for subbase materials because stress and durability conditions differ for various depths in the pavement structure.

Typical current mixture design criteria are presented in the section on current mixture design procedures.

Experience and Evaluation

Mixture design criteria can be validated only on the basis of actual field performance. McDowell's extensive publications (*47–52*) concerning Texas experiences, Anday's summary of Virginia projects (*53*), and McDonald's recent reports (*34,41,54,55*) are examples of extensive validation activities for widely separated geographic areas with drastically different climatic conditions.

Mixture design criteria developed for use with a particular mixture design procedure and geographic location must not be applied indiscriminately to other areas. Careful consideration should be given to all aspects of the problem before adopting any criteria.

CURRENT MIXTURE DESIGN PROCEDURES

Selected current mixture design procedures are summarized. As discussed, mixture design procedures consider specimen preparation, curing conditions, testing procedures, and mixture design criteria. In addition, excellent guidelines relating to mixture design, as well as pavement design and construction, are provided in the two-volume set entitled *Soil Stabilization in Pavement Structures—A User's Manual* (*56,57*). More information can be found by consulting the various references listed in this section.

California Procedure

California's current design procedure (California Test 373) is based on unconfined compressive strength-test data developed for mixtures containing various lime percentages. The first phase of the procedure determines the optimum water content for compaction of lime-treated soil mixtures at various lime contents. The second phase determines the unconfined compressive strength for accelerated cured compacted lime-soil mixtures. The general procedure is as follows:

1. Select several trial lime contents.
2. For each lime content, prepare a minimum of five compacted specimens using various moisture contents. The two-stage mixing procedure requires the addition of one-half the estimated compaction moisture to a dry-mixed sample of lime and soil, mixing no longer than 1 min, and a sealed curing period from 16 to 24 hr at 70°F plus or minus 5°F. The second phase requires the remaining moisture to be added followed by mixing to a uniform consistency.
3. Specimens are compacted using kneading compaction followed by a static load and the optimum moisture content is selected for each lime content.
4. Using the optimum moisture contents, specimens are compacted at each trial lime content. The mixing procedure is as discussed in Step 2 except all required water is added before the sealed curing phase. Compaction is as described in Step 3.
5. The compacted specimens are oven cured in a sealed condition for 7 days at 110°F plus or minus 5°F.
6. The design lime content is selected on the basis of unconfined compressive test results using nominal 4-in. diameter by 4-in. high specimens.

Eades and Grim Procedure

The pH mixture design concept developed by Eades and Grim (*58*) involves, to a certain extent, a strength-based criterion. The basic thrust of the pH procedure is to add sufficient lime to the soil to ensure a pH of 12.4 for sustaining the strength-producing, lime-soil pozzolanic reaction. The pH procedure, as developed by Eades and Grim, is summarized as follows.

1. Representative samples of air-dried, minus Number 40 soil to equal 20 g of oven-dried soil are weighed to the nearest 0.1 g and poured into 150-ml (or larger) plastic bottles with screw tops.
2. Because most soils will require between 2 and 5 percent lime, it is advisable to set up five bottles with lime percentages of 2, 3, 4, 5, and 6. This will ensure, in most cases, that the percentage of lime required can be determined in 1 hr. Weigh the lime to the nearest 0.01 g and add it to the soil. Shake to mix soil and dry lime.
3. Add 100 ml of CO_2-free distilled water to the bottles.
4. Shake the soil-lime and water until there is no evidence of dry material on the bottom. Shake for a minimum of 30 sec.
5. Shake the bottles for 30 sec every 10 min.
6. After 1 hr. transfer part of the slurry to a plastic beaker and measure the pH. The pH meter must be equipped with a Hyalk electrode and standardized with a buffer solution with a pH of 12.00.
7. Record the pH for each of the soil-lime mixtures. If the pH readings go to 12.40, the lowest percentage of lime that gives a pH of 12.40 is the percentage required to stabilize the soil. If the pH does not go beyond 12.30 and 2 percent lime gives the same reading, the lowest percentage that gives a pH of 12.30 is that required

to stabilize the soil. If the highest pH is 12.30 and only 1 percent lime gives a pH of 12.30, additional test bottles should be started with larger percentages of lime.

Thompson and Eades (*59*) demonstrated that for typical Illinois soils, the lime percentage determined by the pH test was approximately the same as the lime percentage producing maximum compressive strength. Recent work by Harty (*60*), however, indicates that the lime percentage obtained from the pH procedure does not produce maximum cured compressive strength for tropical and subtropical soils. There are limitations to the pH procedure: (a) the technique does not establish whether the soil will react with lime to produce a substantial strength increase, and (b) strength data are not generated for use in evaluating mixture quality.

Eades and Grim (*58*) recognized the need for supplemental strength data and have stated: "The 1 hr pH or 'Quick Test' can be used only to determine the lime requirements of a soil for stabilization. Since strength gains are related to the formation of calcium silicates, and their formation varies with the mineralogical components of the soil, a strength test is necessary to show the percentage of strength increase."

Illinois Procedure

The Illinois procedure considers two types of stabilization objectives:

1. Soil-lime stabilization in which the mixture will be utilized as a base or subbase material in the pavement system, and
2. Subgrade modification and expediting construction.

Soil-Lime Stabilization

The mixture design procedure is based on unconfined compressive strength-test data. Specimens with a 2-in. (5.1-cm) diameter and a 4-in. (10.2-cm) height of the natural soil and soil-lime mixtures are prepared at optimum moisture content and maximum dry density (AASHTO T–99). The soil-lime specimens, prepared at various lime treatment levels, are cured for 48 hr at 48.9°C (120°F) before testing.

The compressive strength of the soil-lime mixture with 3 percent lime must be at least 50 psi (34.5 N/cm^2) greater than the compressive strength of the natural soil. The design lime content is designated as the lime percentage above which further increases do not produce significant additional strength. For field construction, the lime content is increased 0.5 to 1.0 percent to offset the effects of field variability. Minimum strength requirements are 100 psi (69 N/cm^2) for subbase and 150 psi (103 N/cm^2) for base course. These minimum strengths relate to AASHTO coefficients of relative strength of 0.12 for subbase materials, and 0.11 for base course materials.

Subgrade Modification

The mixture design procedure for lime modification is based on the effect of lime on the PI of the soil. Optional CBR testing can also be conducted if desired.

AASHTO Methods T–89 and T–90 are utilized to determine the liquid limit, plastic limit, and PI of the soil treated with various percentages of lime. The lime-soil-water mixture is loose cured for 1 hr before testing. A plot of PI versus lime content is prepared. The design lime content may be designated as (a) lime content above which no further appreciable reduction in PI occurs, or (b) a minimum lime content that produces an acceptable PI reduction.

Depending on the stabilization objectives, CBR tests may also be conducted to

evaluate the stability, swell properties of the lime-treated soil, or both. Curing and soaking the CBR specimens before testing is optional depending on the stabilization objectives. If appropriate, the design lime content may be changed based on the CBR data, stability values, or swell properties.

For field construction, the design lime content is increased 0.5 to 1.0 percent to offset the effects of field construction variability.

Oklahoma Procedure

Oklahoma's standard procedure for determining the optimum lime content is the Eades and Grim procedure. As an alternative, a PI reduction test procedure is used as follows. The basic objective of Oklahoma's lime treatment is to modify subgrade soils without any specific strengthening objective.

1. Soil-lime mixtures with lime contents of 3, 5, 7, and 10 percent are prepared at the AASHTO T–99 optimum moisture content for the soil.
2. The soil-lime mixtures are loose cured in a moisture room for 48 hr.
3. The cured soil-lime mixture is then dried in accordance with AASHTO T–87 Paragraph 4(a).
4. The liquid limit, plastic limit, and PI are determined in accordance with AASHTO methods T–89 and T–90, respectively.
5. A plot of PI versus percentage of lime is prepared. The percent lime that reduces the PI by two points per 1 percent increase in lime is considered to be the optimum lime content for the soil-lime mixture. Any lime content at or below the optimum lime content that gives the desired modification may be recommended by the engineer. The PI should be reduced to a maximum value of 10.

South Dakota Procedure

Initial lime requirements are established based on a pH procedure (Test SD 128) similar to the Eades and Grim procedure. Supplemental strength data are developed by evaluating the CBR of various soil-lime and base course-lime combinations compacted at optimum moisture content (AASHTO T–99) to maximum dry density. Unconfined compression tests are also used.

The South Dakota technique (Test SD 107) is similar to AASHTO T–193. If the CBR of the soil-lime and base course-lime mixtures (with no curing except for the 96-hr soaking period) is 3 to 4 times greater than the CBR of the unstabilized materials, the mixtures are considered to be of adequate quality for use as a pavement layer. Consideration is also being given to the requirement that the soil-lime and base course-lime mixtures must have less than one-half of 1 percent of vertical expansion after 30 freeze-thaw cycles and retain 75 percent of the initial strength after freeze-thaw cycling.

The AASHTO coefficient of relative strength is 0.05 for soil-lime mixtures and 0.15 for base course-lime mixtures if the foregoing strength and volume changes are met.

Texas Procedure

The soil-lime mixture design procedure used by the State Department of Highways and Public Transportation is AASHTO T–220, which provides for the determination of the unconfined compressive strength of soil-lime mixtures. The procedure suggests strength criteria of 100 psi (69 N/cm^2) for base construction and 50 psi (34.5 N/cm^2) for subbase construction.

Details of the procedure are included in AASHTO T–220; however, a general outline of the procedure is presented here.

1. Based on the grain size and PI data, the lime percentage is selected from Figure 3-1 (*47*). Note that the percentages in Figure 3-1 should be substantiated by approved testing methods on any particular soil material. A single asterisk (*) indicates that use of the chart for materials with less than 10 percent Number 40 and cohesionless materials (PI less than 3) is excluded. A double asterisk (**) indicates a percentage of relatively pure lime usually 90 percent or more of Ca and Mg hydroxides, or both, and 85 percent or more of which pass the Number 200 sieve. Percentages shown are for stabilizing subgrades and base courses where lasting effects are desired. Satisfactory temporary results are sometimes obtained by the use of as little as one-half of the aforementioned percentages. Reference to cementing strength is implied when such terms as "lasting effects" and "temporary results" are used.
2. Optimum moisture and maximum dry density of the mixture are determined in accordance with appropriate sections of AASHTO T–212 or Tex–113–E. The compactive effort is 50 blows of a 10-lb (4.54-kg) hammer with an 18-in. (45.7-cm) drop.

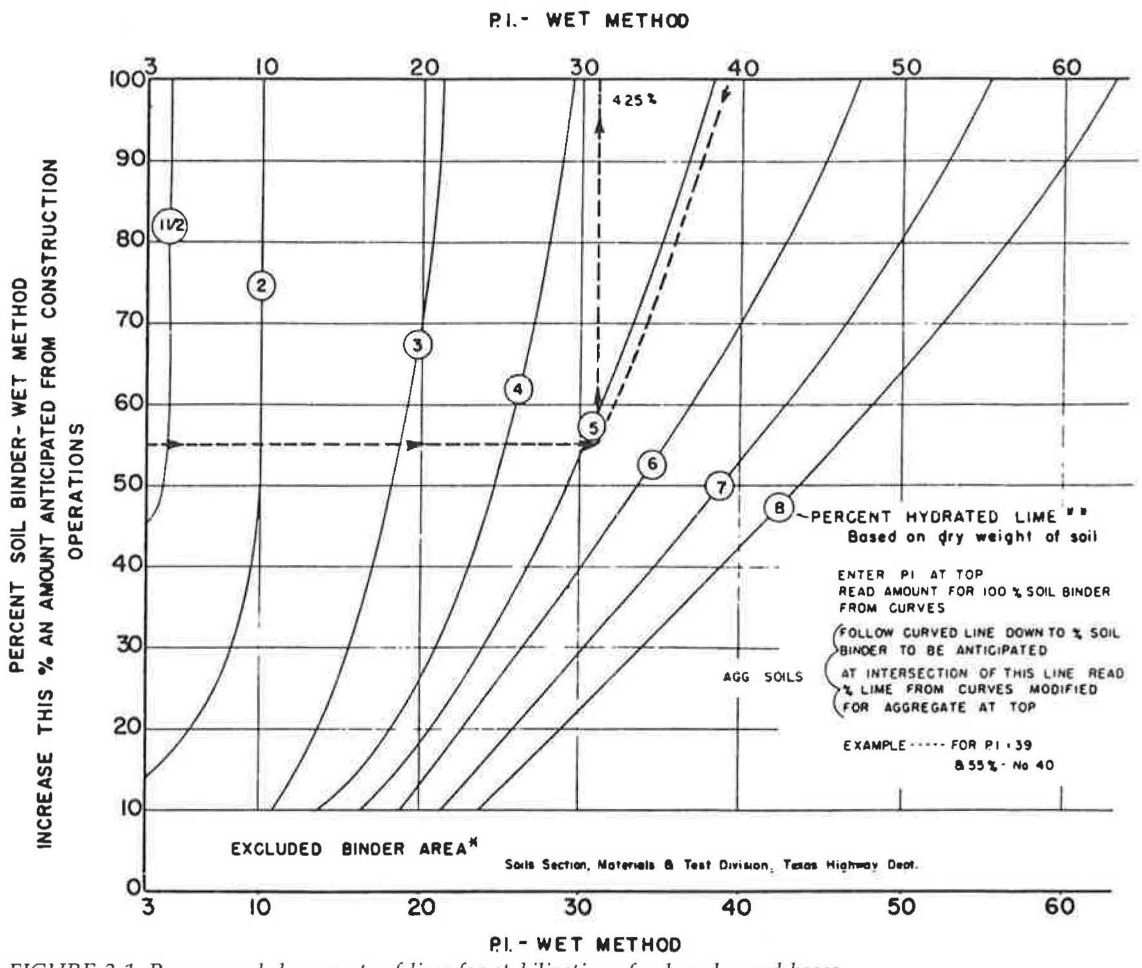

FIGURE 3-1 Recommended amounts of lime for stabilization of subgrades and bases.

3. Test specimens 6 in. (15.2 cm) in diameter and 8 in. (20.3 cm) in height are compacted at optimum moisture content to maximum dry density.
4. The specimens are placed in a triaxial cell (AASHTO T–212 or Tex–121–E) and cured in the following manner:
   a. Allow the specimens to cool to room temperature,
   b. Remove cells and dry at a temperature not exceeding 60°C (140°F) for about 6 hr or until one-third to one-half of the molding moisture has been removed,
   c. Cool the specimens for at least 8 hr, and
   d. Subject the specimens to capillarity (AASHTO T–212 Section 6 or Tex–121–E) for 10 days.
5. The cured specimens are tested in unconfined compression in accordance with AASHTO T–212 Sections 7 and 8 or Tex–117–E.

The results of the unconfined compression strength testing can be used for the purpose of substantiation.

Thompson Procedure

Thompson (*61*) has developed a mixture design process for lime-treated soils in which different procedures are proposed for lime modified soils and soil-lime mixtures.

The lime modification procedure is utilized when the stabilization objectives are to expedite construction and produce subgrade modification, (e.g., CBR increase, decreased swell potential, and decreased plasticity). Soil-lime mixtures that display significant compressive-strength increases, 50 psi (34.5 N/cm^2) minimum, can be utilized as base and subbase materials depending on the soil-lime mixture properties and pavement service requirements.

A flow diagram shows the mixture design process in Figure 3-2 (*61*). The following refers to the superscript numbers shown on the flow diagram:

1. All specimens are compacted at optimum water content to maximum dry density. Lime treatment level for (b) may be 5 percent or as determined by the pH procedure. (See Note 6.)
2. PI tests are conducted 1 hr after mixing the lime-soil-water mixture. Mixture is not cured before testing.
3. In some cases more closely spaced treatment levels may be appropriate.
4. Criteria (a) or (b) may be applied depending on the stabilization objective.
5. Conduct tests on design lime content. Curing of CBR specimens before soaking is optional depending on stabilization objective. If swell is not reduced to a satisfactory level, additional CBR tests may be conducted at higher lime contents. Design lime content may be increased if further swell reduction is obtained. Swell considerations are of great importance for lime-modified subgrades.
6. Specimens are compacted at optimum moisture content to maximum dry density. Additional or different (or both) lime percentages may be required for some soils. An estimate of approximate optimum lime content may be obtained by applying the pH test developed by Eades and Grim (*58*).

Quality criteria for the soil-lime mixtures were established based on considerations of pavement structural behavior and durability requirements. The soil-lime quality criteria are summarized in Table 3-1 (*61*).

The development of the mixture design process and the detailed testing procedures are given elsewhere (*61*). It is emphasized that the lime-modified soil mixture design process can be utilized for reactive soils if the stabilization objectives are primarily to expedite construction or modify the subgrade.

Virginia Procedure

Virginia's mixture design procedure, VTM–11 Virginia Test Method for Lime Stabilization, is based on the cured compressive strength of soil-lime mixtures stabilized with various amounts of lime. The procedure is summarized as follows:

1. Proctor-sized specimens at various lime percentages are prepared at approximately optimum moisture content and maximum dry density (AASHTO T–99), and a compaction test is conducted with 6 percent lime.
2. Specimens are cured in sealed containers at high humidity for 72 hr at 48.9°C (120°F).
3. The soil-lime specimens are tested in unconfined compression using a loading rate of 2,400 lb/min (1089 kg/min) or approximately 19 psi/min (1.3 kg/cm²/min).
4. Virginia criteria to determine the appropriate percentage of lime are based on cost effectiveness and the benefit derived.

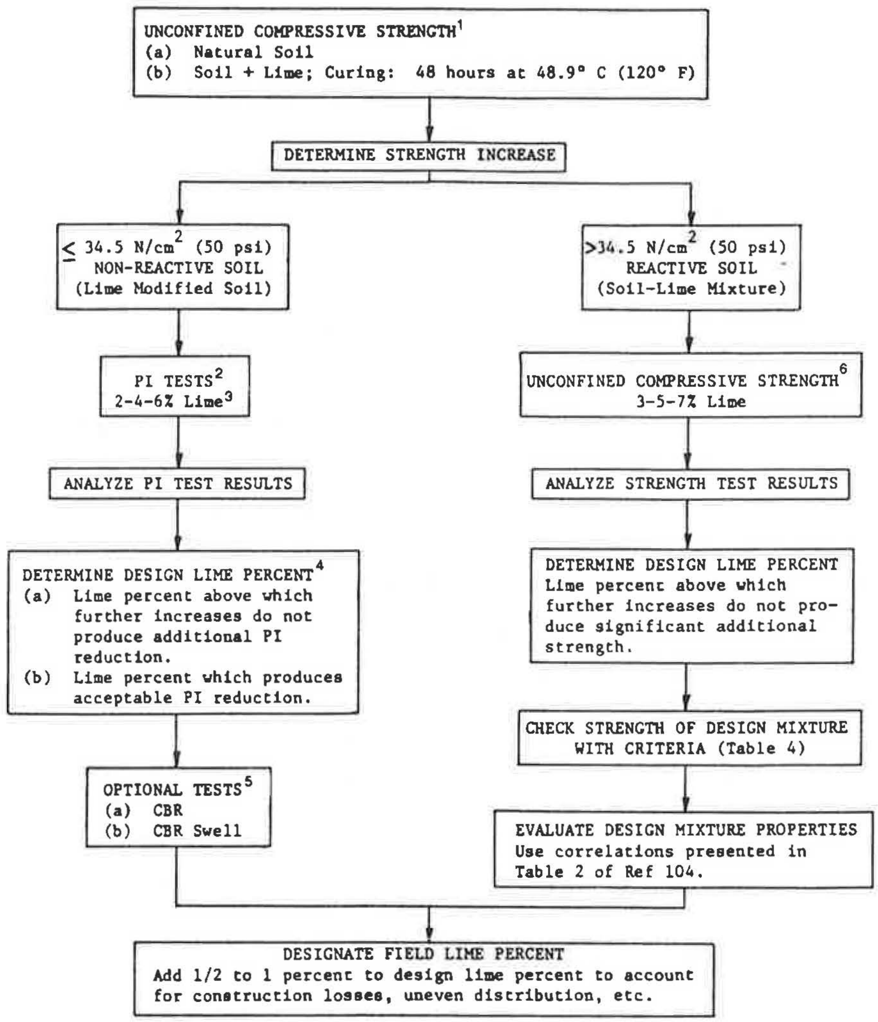

FIGURE 3-2 Proposed mixture design process for lime-treated soils.

TABLE 3-1 Tentative Soil-Lime Mixture Compressive Strength Requirements

Anticipated Use	Residual Strength Requirement (psi)[a]	Strength Requirements for Various Anticipated Service Conditions[b]			
		Extended Soaking for 8 days (psi)	Cyclic Freeze-Thaw[c]		
			3 Cycles (psi)	7 Cycles (psi)	10 Cycles (psi)
Modified Subgrade					
	20	50	50	90 50	120
Subbase					
Rigid pavement	20	50	50	90 50[d]	120
Flexible pavement by cover thickness[e]					
10 in.	30	60	60	100 60[d]	130
8 in.	40	70	70	100 75[d]	140
5 in.	60	90	90	130 100[d]	160
Base					
	100[f]	130	130	170 150[d]	200

Note: 1 psi = 0.6895 N/cm^2; 1 in. = 2.5 cm.
[a] Minimum anticipated strength following first winter exposure.
[b] Strength required at termination of field curing following construction to provide adequate residual strength.
[c] Number of freeze-thaw cycles expected in the soil-lime layer during the first winter of service.
[d] Freeze-thaw strength losses based on 10 psi/cycle except for 7-cycle values indicated by superscript *d*, which were based on a previously established regression equation.
[e] Total pavement thickness overlying the subbase. The requirements are based on the Boussinesq stress distribution. Rigid pavement requirements apply if cemented materials are used as base courses.
[f] Flexural strength should be considered in thickness design.

ACCELERATED CURING CAUTIONS

Because the strength of lime-stabilized soil is both time and temperature dependent, the mixture design process is complicated. It is common to base the structural design of a lime-stabilized layer on the engineering properties expected after several weeks (28 days) of compacted curing under field environmental conditions. However, mixture design procedures that require four or more weeks are not feasible. Curing schemes using elevated temperatures have been used in the laboratory to develop mixture designs based on accelerated formation of pozzolanic reactive products. Recent research (*12,62,63*) indicates that if accelerated curing temperatures are too high, the pozzolanic compounds formed during laboratory curing could differ substantially from those that would develop in the field. Generally, elevated curing temperatures in excess of 120°F should be avoided with accumulating research evidence indicating that 105°F at various curing times is appropriate without introducing pozzolanic reactive products that significantly differ from those expected during field curing.

SUMMARY

Design lime contents are usually based on an analysis of the effect of varying lime percentages on selected engineering properties of the soil-lime mixture. Usually, the basic components of a mixture design procedure are:

1. Method for preparing the soil-lime mixture,
2. Procedure for preparing and curing specimens,
3. Testing procedures for evaluating a selected property or properties of the cured soil-lime mixture, and
4. Appropriate criteria for establishing the design lime content.

It is important to note that different design lime contents for the same soil may be established depending on the objectives of the lime treatment and the mixture design procedure utilized. Mixture design procedures should be flexible enough to allow the exercise of judgment when unusual stabilization objectives are contemplated.

CHAPTER 4
Lime Stabilization Construction

The modern version of lime stabilization is less than 40 years old, but considerable advancement has been made in construction procedures during these past 4 decades. The progress of this method of stabilization is a result of the efforts of many engineers and scientists summarized as follows:

1. Basic and applied research by numerous state highway departments, governmental agencies, and universities;
2. Education through worldwide publication of research studies and construction reports of actual lime stabilization projects; and
3. Equipment manufacturer's recognition of the potential of lime stabilization and development of equipment to meet the needs of the contractor. Thirty-five years ago there were two basic stabilizers that could be adapted to lime stabilization, but today there are approximately 20 different types of equipment designed primarily for this stabilization.

With the growth of lime stabilization throughout the world for many climatic conditions, a diversity of applications has developed and a variety of construction techniques has evolved. This variation has been due to such factors as type of soil, degree of stabilization required, complexity of project, ecological restraints, and type of pavement design. For example, some heavy clay soils are very reactive to lime and can be completely pulverized with only one pass of a travelling mixing unit; however, this is the exception to the rule because the stabilization of a heavy gumbo clay usually requires much more manipulation and curing than a low-plastic granular material. Modification of soil, such as drying out of wet soil with lime to expedite construction, is less involved than completely stabilizing a heavy clay to be used as a part of the pavement structure.

Projects may range from maintenance activities for which only a few bags of lime are required (Figure 4-1) to vast interstate highways or airfield pavements requiring thousands of tons of bulk lime. Because of dusting, projects located in urban areas generally require the use of lime slurry rather than dry lime. Therefore, with the growing emphasis on ecology the trend is toward a greater use of a lime slurry and some engineers are now discouraging the use of dry lime except in very localized areas.

Furthermore, when lime is used in pavement design to reduce overall thickness, the stabilized layer must be built under tight construction specifications, whereas requirements are more lenient when lime is merely used to form a working table.

Regardless of the specific application of soil-lime, the following basic steps are involved in the construction procedure: soil preparation, lime spreading, mixing and watering, compaction and finishing, and curing. These basic steps, along with the more significant variations, are discussed in detail. Because this is a state-of-the-art report, undoubtedly there will be more variations as lime stabilization continues to expand throughout the world.

LIME STABILIZATION METHODS

Basically, there are three recognized lime stabilization methods: in-place mixing, plant mixing, and pressure injection.

In-Place Mixing

In-place mixing may be subdivided into three methods:

1. Mixing lime with the existing materials already a part of the construction site or pavement (Figure 4-2),
2. Off-site mixing in which lime is mixed with borrow and the mixture is then transported to the construction site for final manipulation and compaction (Figure 4-3), and
3. Mixing in which the borrow source soil is hauled to the construction site and processed as in the first method.

The following procedures are for in-place mixing:

1. One increment of lime is added to clays or granular base materials that are easy to pulverize. The material is mixed and compacted in one operation, and no mellowing period is required.
2. One increment of lime is added and the mixture is allowed to mellow for a period of 1 to 7 days to assist in breaking down heavy clay soils.
3. One increment of lime is added for soil modification and pulverization before treatment with cement or asphalt.

FIGURE 4-1 Application of lime by the bag for a small maintenance project in Texas.

FIGURE 4-2 In-place mixing of lime with existing base and paving material on city street in Texas.

4. One increment of lime is added to produce a working table. Proof rolling is required instead of pulverization and density requirements.
5. Two increments of lime are added for soils that are extremely difficult to pulverize. Between the applications of the first and second increments of lime, the mixture is allowed to mellow.
6. Deep stabilization which has been accomplished by one of two approaches (*28*).
   a. One increment of lime is applied to modify soil to a depth of 24 in. (Figures 4-4 to 4-6). Greater depths are possible but to date have not been attempted. A second increment of lime is added to the top 6 to 12 in. (15 to 30 cm) for

FIGURE 4-3 *Off-site mixing pads for Mississippi River levee repair project in Arkansas.*

FIGURE 4-4 *Deep stabilization of access road at Dallas–Fort Worth Airport. After lime spreading the plow cuts 24 in. deep.*

FIGURE 4-5 *Root plow for scarifying to a depth of 18 in.*

complete stabilization. Plows and rippers are used to break down the large clay chunks in the deep treatment. Heavy disc harrows and blades are also used in pulverization of these clay soils. In frost zones, the use of small quantities of lime for soil modification under some circumstances may result in a frost-susceptible material that in turn can produce a weak sublayer.

b. One increment of lime is applied for complete stabilization to a depth of 18 in. (46 cm). Mechanical mixers are now available to pulverize the lime-clay soil to the full depth by progressive cuts as follows: first-pass cut to a depth of 6 in. (15 cm), second to 9 in. (23 cm), third to 12 in. (30 cm), fourth to 15 in. (38 cm), and then a few passes to a depth of 18 in. (46 cm) to accomplish full pulverization. The full 18 in. (46 cm) is compacted from the top by vibratory and conventional heavy rollers.

Plant Mixing

The plant-mix operation usually involves hauling the soil to a central plant where lime, soil, and water are uniformly mixed and then transported to the construction site for further manipulation (Figures 4-7 to 4-9).

FIGURE 4-6 Scarifying existing clay subgrade with lime on city street project in California.

FIGURE 4-7 Lime-treated gravel with lime fed by screw conveyor in South Dakota.

FIGURE 4-8 Lime-cement-fly ash aggregate base course at Newark Airport.

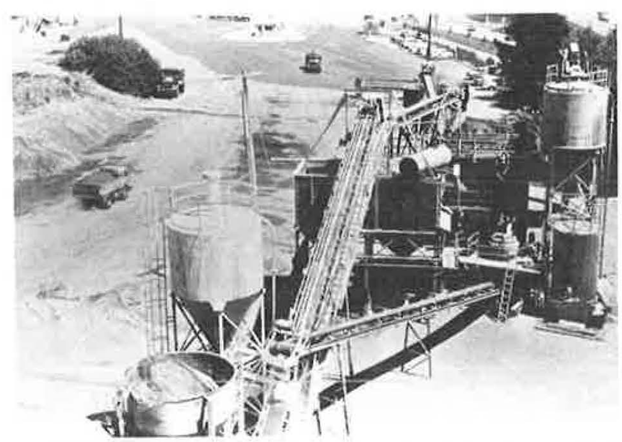

FIGURE 4-9 Enclosed silo holds lime for adding to marginal crushed stone base material in California.

The amount of lime for either method is usually predetermined by test procedures. Specifications may be written to specify the actual strength gain required to upgrade the stabilized soil, and notations can be made on the plans concerning the estimated percent of lime required. This note should also stipulate that changes in lime content may be necessary to meet changing soil conditions encountered during construction.

Pressure Injection

Pressure injections of lime slurry to depths of 7 to 10 ft (2 to 3 m), for control of swelling and unstable soils on highways (Figure 4-10) and under building sites, are usually placed on 5-ft (1.5-m) spacings, and attempts are made to place horizontal seams of lime slurry at 8- to 12-in. (20- to 30-cm) intervals. The top 6- to 12-in. (15- to 30-cm) layer should be completely stabilized by conventional methods.

Research reported by Petry et al. (*64*) utilized a statistically designed field plot at the Dallas–Fort Worth regional airport. Changes in 20 soil parameters were studied before and after single- and double-stage lime slurry pressure injections to an effective depth of 7 ft (2 m). Statistically significant reductions at the 5 percent level in percent swell and swelling pressure were measured after both injection treatments.

Pressure injection technology as shown in Figure 4-11, has also been successfully applied to railroad roadbeds (*65, 66*). Blacklock (*67*) has also reported development of a lime slurry glaze method as an improved laboratory evaluation procedure. Other laboratory-oriented soil testing procedures are discussed in a handbook oriented for railroad applications (*65*). Additional general information and details can be obtained elsewhere (*68–71*).

CONSTRUCTION STEPS

Soil Preparation

The in-place subgrade soil should be brought to final grade and alignment. The finished grade elevation may require some adjustment because of the potential fluff action of the lime-stabilized layer resulting from the fact that some soils tend to increase in volume when mixed with lime and water. This volume change may be exaggerated when the soil-lime is remixed over a long period of time, especially at moisture contents less than optimum moisture. The fluff action is usually minimized

FIGURE 4-10 Lime slurry pressure injection (LSPI) rig treating a failed highway slope.

if adequate water is provided and mixing is accomplished shortly after lime is added. For soils that tend to fluff with lime, the subgrade elevation should be lowered slightly or the excess material trimmed. Trimming can usually be accomplished by blading the material onto the shoulder of embankment slopes.

The blading operation is desirable to remove the top 0.25 in. (6.4 mm) because this material often is not well cemented due to lime loss experienced during construction. Excess rain and construction water may wash lime from the surface, and carbonation of lime may occur in the exposed surface.

If dry lime is used, ripping or scarifying to the desired depth of stabilization can be accomplished either before or after lime is added (Figure 4-6). If the lime is to be applied in a slurry form, it is desirable to scarify prior to the addition of lime.

Lime Application

Dry Hydrated Lime

Dry lime can be applied either in bulk or by bag. The use of bagged lime is generally the simplest but also the most costly method of lime application. Bags of 50 lb (22.7 kg) are delivered in dump or flatbed trucks and placed by hand to give the required distribution (Figure 4-1). After the bags are placed they are slit and the lime is dumped into piles or transverse windrows across the roadway. The lime is then levelled either by hand raking or by means of a spike-tooth harrow or drag pulled by a tractor or truck. Immediately after, the lime is sprinkled to reduce dusting.

The major disadvantages of the bag method are the higher cost of lime because of bagging costs, greater labor costs, and slower operations. Nevertheless, bagged lime is often the most practical method for small projects or for projects in which it is difficult to utilize large equipment.

For large stabilization projects, particularly where dusting is no problem, the use of bulk lime has become common practice. Lime is delivered to the job in self-unloading transport trucks (Figure 4-12). These trucks are large and efficient, capable

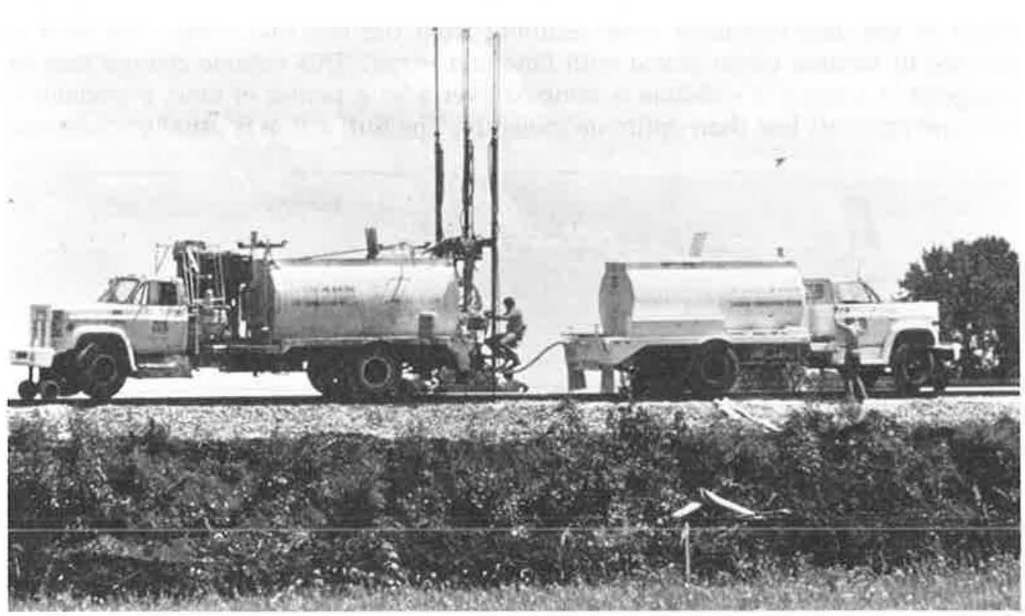

FIGURE 4-11 LSPI unit and slurry tank truck on railroad maintenance project.

of hauling 15 to 24 tons (13 300 to 21 800 kg). One type is equipped with one or more integral screw conveyors that discharge at the rear. In recent years pneumatic trucks have increased in popularity and are preferred over the older auger-type transports. With the pneumatic units the lime is blown from the tanker compartments through a pipe or hose to a cyclone spreader or to a pipe spreader bar mounted at the rear (Figure 4-13). Bottom-dump hopper trucks have also been tried, but they are undesirable because of difficulty in unloading and obtaining a uniform rate of discharge.

With the auger trucks, spreading is handled by means of a portable, mechanical-type spreader attached to the rear (Figure 4-14) or through metal downspout chutes

FIGURE 4-12 Application of lime by a bulk pneumatic truck for levee repair project in Arkansas.

FIGURE 4-13 Bulk pneumatic truck spreading lime from bar spreader in Wisconsin.

FIGURE 4-14 Distribution of quicklime from mechanical spreader on city street base project in California.

or flexible rubber boots extending from the screw conveyors. The mechanical spreaders incorporate belt, screw, rotary vane, or drag-chain conveyors to distribute the lime uniformly across the spreader width. When boots or spouts are used instead, the lime is deposited in windrows; but because of lime's lightness and flowability, the lime becomes distributed rather uniformly across the spreading lane. Whether mechanical spreaders, downspouts, or boots are used, the rate of lime application can be regulated by varying the spreader opening, spreader drive speed, or truck speed so that the required amount of lime can be applied in one or more passes.

With the pneumatic trucks, spreading is generally handled with a cyclone spreader mounted at the rear, which distributes the lime through a split chute or with a spreader bar equipped with several large downspout pipes. Finger-tip controls in the truck cab permit the driver to vary the spreading width by adjusting the air pressure. Experienced drivers can adjust the pressure and truck speed so that accurate distribution can be obtained in one or two passes.

When bulk lime is delivered by rail, a variety of conveyors can be used for transferring the lime to transport trucks; these include screw, belt, or drag-chain conveyors, bucket elevators, and screw elevators. The screw-type conveyors are most commonly used, with large diameter units of 10 to 12 in. (25.4 to 30.5 cm) being recommended for high-speed unloading. To minimize dusting, all types of conveyors should be enclosed. Rail-car unloading is generally facilitated by means of poles and mechanical or air-type vibrators.

Lime has also been handled through permanent or portable batching plants, in which case the lime is weigh-batched before loading. Generally, a batching plant setup would only be practical on exceptionally large jobs.

Obviously, the self-unloading tank truck is the least costly method of spreading lime, because there is no rehandling of material and large payloads can be carried and spread quickly.

Dry Quicklime

Quicklime may be applied in bags or bulk. Because of higher cost, bagged lime is only used for drying of isolated wet spots or on small jobs. The distribution of bagged quicklime is similar to that of bagged hydrate, except that greater safety emphasis is needed. First the bags are spaced accurately on the area to be stabilized, and after spreading, water is applied and mixing operations started immediately.

FIGURE 4-15 Spreading of granular quicklime on canal relining project in California.

FIGURE 4-16 Slurry mixing tank using recirculating pump for mixing hydrate and water.

The fast watering and mixing operation helps minimize the danger of burns. Quicklime may be applied in the form of pebbles of approximately ⅜ in. (9.5 mm), granular, or pulverized. The first two are more desirable because less dust is generated during spreading.

Bulk quicklime may be spread by self-unloading auger or pneumatic transport trucks, similar to those used for dry hydrate. However, because of its coarser size and higher density, quicklime may also be tailgated from a regular dump truck with tailgate opening controls to ensure accurate distribution (Figure 4-15).

Because quicklime is anhydrous and generates heat on contact with water, special care should be taken during stabilization to avoid lime burns. Where quicklime is specified, the contractor should provide the engineer with a detailed safety program covering precautions and emergency treatment available on the jobsite. The program should include protective equipment for eyes, mouth, nose, and skin, as well as a first-aid kit with an eyeball wash. This protective equipment should be available on the jobsite during spreading and mixing operations. The contractor should actively enforce this program for the protection of the workers and others in the construction area.

Slurry Method

In this method either hydrated lime or quicklime and water are mixed into a slurry. With quicklime, the lime is first slaked and excess water added to produce the slurry.

Slurry Made with Hydrated Lime

This method was first used in the 1950s and is currently very popular, especially where dust from using dry lime is a problem. The hydrated lime-water slurry is mixed either in a central mixing tank (Figure 4-16), jet mixer (Figure 4-17), or in a tank truck. The slurry is spread over the scarified roadbed by a tank truck equipped with spray bars (Figures 4-18 and 4-19). One or more passes may be required over a measured area to achieve the specified percentage based on lime solids content. To

FIGURE 4-17 Jet slurry mixing plant on a city street project in Texas.

prevent runoff and consequent nonuniformity of lime distribution that may occur under certain conditions, it may be necessary to mix the slurry and soil immediately after each spreading pass (Figure 4-20).

A typical slurry mix proportion is 1 ton (907 kg) of lime and 500 gal (1.9 m^3) of water, which yields about 600 gal (2.3 m^3) of slurry containing 31 percent lime solids. At higher concentrations there is difficulty in pumping and spraying the slurry. Forty percent solids is a maximum pumpable slurry.

The actual proportion used depends on the percentage of lime specified, type of soil, and its moisture condition. When small lime percentages are required, the slurry proportions may be reduced to 1 ton (907 kg) of lime per 700 to 800 gal (2.6 to 3.0 m^3) of water. Where the soil moisture content is near optimum, a stronger lime concentration would normally be required.

In plants employing central mixing, agitation is usually accomplished by using compressed air and a recirculating pump, although pug mills have also been used. The most typical slurry plant incorporates slurry tanks large enough to handle whole tank truck loads of hydrated lime of approximately 20 tons (18 100 kg). For example, on one job two 15,000-gal (57-m^3) tanks, 10-ft diameter by 26-ft length (3 m by 8 m) were used, each fitted with an 8-in. (20-cm) perforated air line mounted along the bottom. The air line was stopped 18 in. (46 cm) short of the end wall, thereby providing maximum agitation in the lime-feeding zone. A typical batch consisted of 10,000 gal (38 m^3) of water (charged first) and 20 tons (18 100 kg) of lime, producing about 12,000 gal (45 m^3) of slurry in less than 25 min. Loading of the tank trucks was handled by a standard water pump, with one slurry tank being unloaded while the slurry was being mixed in the other tank.

On another job the contractor used a similar tank and air line, but in addition a 4-in. (10-cm) recirculating pump was used for mixing; the same pump loaded the tank trucks. To keep the lime from settling, the contractor devised a hand-operated scraper fitted with air jets.

The newest and most efficient method of slurry production, which eliminates batching tanks, involves the use of a compact jet slurry mixer. Water at 70 psi (5 kg/cm^2) and hydrated lime are charged continuously in a 65:35 (weight) ratio into the jet mixing bowl where slurry is produced instantaneously. The mixer and auxiliary equipment can be mounted on a small trailer and transported to the job readily, giving great flexibility to the operation (72).

FIGURE 4-18 Spreading of lime slurry.

In the third type of slurry setup, measured amounts of water and lime are charged separately to the tank truck, with the slurry being mixed in the tank either by compressed air or by a recirculating pump mounted at the rear. The water is metered and the lime proportioned volumetrically or by means of weight batchers. Both portable and permanent batching plants are used. Mixing with air is accomplished at the plant. The air jets are turned on during the loading operation, and remain on until the slurry is thoroughly mixed which takes about 10 to 15 min. The use of a recirculating pump, however, permits mixing to occur during transit to the job. Usually 2-, 3-, or 4-in. (5-, 8-, or 10-cm) pumps are used in this operation, with the slurry being recirculated through the tank by means of a perforated longitudinal pipe extending the length of the tank and capped at one end.

FIGURE 4-19 Recirculation pump on top of a 6,000-gal wagon agitates slurry.

FIGURE 4-20 Grader-scarifier cutting slurry into stone base.

Spreading from the slurry distributors is effected by gravity or by pressure spray bars, the latter being preferred because of better distribution. The use of spray deflectors is also recommended for good distribution. The general practice in spreading is to make either one or two passes per load. However, several loads may be needed in order to distribute the required amount of lime. The total number of passes will depend on the lime requirement, optimum moisture of the soil, and type of mixing employed. Windrow mixing with the grader generally requires several passes.

Double Application of Lime

In some areas where extremely plastic, gumbo clay (PI 50+) abounds, it may prove advantageous to add the requisite amount of lime in two increments to facilitate adequate pulverization and obtain complete stabilization. For example, 2 or 3 percent lime is added first, partially mixed, then the layer is sealed and allowed to cure for up to a week. The remaining lime is then added preparatory to final mixing. The first application mellows the clay and helps in achieving final pulverization and the second application completes the lime-treatment process.

Slurry Made With Quicklime

A recent unit developed for making lime slurry from quicklime is the Portabatch slaker (Figure 4-21). This unit consists of a 10-ft diameter by 40-ft tank that incorporates a 5-ft diameter single shaft agitator turned by a 100-hp diesel engine (*73*). The batch slaker can handle 20 to 25 tons of quicklime and about 25,000 gal of water, producing the slurry in about 1 to 1.5 hr. Because of the exothermic action of quicklime in water, the slurry is produced at a temperature of about 185°F.

Advantages and Disadvantages of Different Types of Application

Some of the advantages and disadvantages of the various lime application procedures are listed here.

1. Dry hydrated lime:
   a. Advantages
      - Dry lime can be applied two or three times faster than a slurry.
      - Dry lime is very effective in drying out soils.
   b. Disadvantages
      - Dry lime produces a dusting problem that makes its use undesirable in urban areas.

FIGURE 4-21 Portabatch lime slaker on Interstate highway project in North Carolina.

- The fast drying action of the dry lime requires an excess amount of water during the dry, hot seasons.

2. Dry quicklime:
   a. Advantages
      - More economical as it contains approximately 25 percent more available lime.
      - Greater bulk density for smaller-sized storage silos.
      - Faster drying action in wet soils.
      - Faster reaction with soils.
      - Construction season can be extended, in both spring and fall, because of faster drying.

   b. Disadvantages
      - Field hydration less effective than commercial hydrators, producing a coarser material with poorer distribution in soil mass.
      - Quicklime requires more water than hydrate for stabilization, which may present a problem in dry areas.
      - Greater susceptibility to skin and eye burns.

3. Slurry lime:
   a. Advantages
      - Dust-free application is more desirable from an environmental standpoint.
      - Better distribution is achieved with the slurry.
      - In the lime slurry method, the lime spreading and sprinkling operations are combined, thereby reducing job costs.
      - During summer months slurry application prewets the soil and minimizes drying action.
      - The added heat when slurry is made from quicklime speeds drying action, which is especially desirable in cooler weather.

   b. Disadvantages
      - Application rates are slower. High capacity pumps are required to achieve acceptable application rates.
      - Extra equipment is required, therefore, costs are higher.
      - Extra manipulation may be required for drying purposes during cool, wet, humid weather, which could occur during the fall, winter, and spring construction season.
      - Not practical for use with very wet soils.

Pulverization and Mixing

To obtain satisfactory soil-lime mixtures adequate pulverization and mixing must be achieved. For heavy clay soils two-stage pulverization and mixing may be required, but for other soils one-stage mixing and pulverization may be satisfactory. This difference is primarily due to the fact that the heavy clays are more difficult to break down.

Two-Stage Mixing

Construction steps in two-stage mixing consist of preliminary mixing, moist curing for 24 to 48 hr (or more), and final mixing or remixing. The first mixing step distributes the lime throughout the soil, thereby facilitating the mellowing action. For maximum chemical action during the mellowing period, the clay clods should be less than 2 in. (5 cm) in diameter. Before mellowing the soil should be sprinkled liberally to bring it up to at least two percentage points above optimum moisture in order to aid

the disintegration of clay clods. The exception to excess watering would be in cool, damp weather when evaporation is at a minimum. In hot weather, however, it may be difficult to add too much water.

After preliminary mixing, the roadway should be sealed lightly with a pneumatic roller as a precaution against heavy rain, because the compacted subgrade will shed water, thereby preventing moisture increases that might delay construction. Generally, in 24 to 48 hr the clay becomes friable enough so that desired pulverization can be easily attained during final mixing. Additional sprinkling may be necessary during final mixing to bring the soil to optimum moisture or slightly above (Figure 4-22). In hot weather more than optimum moisture is needed to compensate for the loss through evaporation.

Although disc harrows (Figure 4-23) and grader scarifiers are suitable for preliminary mixing, high-speed rotary mixers (Figures 4-24 to 4-26) or one-pass travel plant mixers (Figure 4-2) are required for final mixing. Motor graders are generally unsatisfactory for mixing lime with heavy clays.

One-Stage Mixing

Both blade and rotary mixing, or a combination, have been used successfully in projects involving granular base materials. However, rotary mixers are preferred for more uniform mixing, finer pulverization, and faster operation. They are generally required for highly plastic soils that do not pulverize readily and for reconstructing worn-out roads in order to pulverize the old asphalt.

FIGURE 4-22 Watering of lime-treated clay on airport project in Kansas City, Missouri.

FIGURE 4-24 Rotary mixer on project in San Jose, California.

FIGURE 4-23 Mixing with a disc harrow.

FIGURE 4-25 Train of rotary mixers at Dallas–Fort Worth Airport.

Blade Mixing

When blade mixing is used in conjunction with dry lime, the material is generally bladed into two windrows, one on each side of the roadway. Lime is then spread on the inside of each windrow or down the center line of the road. The soil is then bladed to cover the lime. After the lime is covered, the soil is mixed dry by blading across the roadway. After dry mixing is completed, water is added to slightly above the optimum moisture content and additional mixing is performed. To ensure thorough mixing by this method, the material should be handled on the mold board at least three times.

When blade mixing is used with the slurry method, the mixing is done in thin lifts that are bladed to windrows. One practice is to start with the material in a center windrow, then blade aside a thin layer after the addition of each increment of slurry, thereby forming side windrows. The windrowed material is then bladed back across the roadway and compacted, provided that its moisture content is at optimum.

A second practice is to (a) start with a side windrow, then blade a thin 2-in. (5-cm) layer across the roadway, and (b) add an increment of lime, then blade this layer to a windrow on the opposite side of the road. On one job this procedure was repeated several times until all the material was mixed and bladed to the new windrow. Because only one-half of the lime had been added at this time, the process was repeated, moving the material back to the other side. This procedure is admittedly slow, but it provides excellent uniformity.

Rotary Mixing

When high-speed rotary mixers are used, the lime is generally spread evenly on the entire roadway, and mixing starts from the top down. Depending on the type of equipment used and the soil involved, complete mixing can normally be accomplished

FIGURE 4-26 Rotary mixer on primary road project.

in one to three passes. If needed, water is added during mixing to obtain the desired moisture content, which is generally optimum. The water may be added by sprinkling trucks or by spraying into the mixing chamber of the mixer. The latter method has considerable merit because the intimate contact of lime, water, and soil facilitates chemical breakdown and pulverization.

Central Mixing

Premixing lime with granular base materials is becoming popular on new construction projects, particularly where submarginal gravels are used. Because the gravel has to be processed anyway to meet gradation specifications, it is a relatively simple matter for the contractor to install a lime bin, feeder, and pug mill at the screening plant. On one project a small pug mill was installed at the head pulley of the collecting belt conveyor (Figure 4-7) and at another operation a larger pug mill plant was utilized (Figure 4-8). The general practice is to add the optimum moisture at the pug mill, thereby permitting immediate compaction after laydown. Figure 4-9 shows a crushed-stone plant in California where lime was added to upgrade a clay bearing crushed stone.

Pulverization and Mixing Requirements

Pulverization and mixing requirements are generally specified in terms of percentages passing the 1.5-in. or 1-in. screen and the Number 4 sieve. Typical requirements are 100 percent passing the 1-in., and 60 percent passing the Number 4 sieve, exclusive of nonslaking fractions. However, in some applications the requirements are relaxed. For example, the South Dakota Highway Department only requires 100 percent passing the 1.5-in. screen with no requirement for the Number 4 sieve. Other specifications may only require 40 to 50 percent passing the Number 4 sieve.

In certain expedient construction operations formal requirements are eliminated, and the "pulverization and mixing to the satisfaction of the engineer" clause is employed.

Compaction

For maximum development of strength and durability, lime-soil mixtures should be properly compacted. Many agencies require at least 95 percent of AASHTO T–99 density for subbases and 98 percent for bases. Some agencies have required 95

FIGURE 4-27 Self-propelled sheepsfoot roller.

FIGURE 4-28 Double sheepsfoot roller.

percent AASHTO T–180 maximum density. Although such densities can be achieved for more granular soil-lime mixtures, it is difficult to achieve this degree of compaction for lime-treated, fine-grained soils.

If a thick soil-lime lift is to be compacted in one lift, many specifications require 95 percent of AASHTO T–99 maximum density in the upper 6 to 9 in. (15 to 23 cm), and lower densities are accepted in the bottom portion of the lift. To achieve high densities compacting at approximately optimum moisture content with appropriate compactors is necessary. Granular soil-lime mixtures are generally compacted as soon as possible after mixing, although delays of up to 2 days are not detrimental, especially if the soil is not allowed to dry out and lime is not allowed to carbonate. Fine-grained soils can also be compacted soon after final mixing, although delays of up to 4 days are not detrimental. When longer delays (2 weeks or more) cannot be avoided, it may be necessary to incorporate a small amount of additional lime into the mixture (0.5 percent) to compensate for losses due to carbonation and erosion.

Various rollers and layer thicknesses have been used in lime stabilization. The most common practice is to compact in one lift by first using the sheeps-foot roller (Figures 4-27 to 4-28) until it "walks out," and then using a multiple-wheel pneumatic roller (Figure 4-29). In some cases, a flat wheel roller is used in finishing. Single lift compaction can also be accomplished with vibrating impact rollers (Figure 4-30) or heavy pneumatic rollers, and light pneumatic or steel rollers used for finishing. When light pneumatic rollers are used alone, compaction is generally done in thin lifts usually less than 6 in. (15 cm). Slush rolling of granular soil-lime mixtures with steel rollers is not recommended. During compaction, light sprinkling may be required, particularly during hot, dry weather, to compensate for evaporation losses.

Curing

Maximum development of strength and durability also depends on proper curing. Favorable temperature and moisture conditions, and the passage of time are required for curing. Temperatures higher than 4.4°C to 10°C (40°F to 50°F), and moisture contents around optimum are conducive to curing. Although some specifications require a 3- to 7-day undisturbed curing period, other agencies permit the immediate placement of overlying paving layers if the compacted soil-lime layer is not rutted or distorted by the equipment. This overlying course maintains the moisture content of the compacted layer and is an adequate medium for curing.

Two types of curing can be employed: moist and asphaltic membrane. In the first,

FIGURE 4-29 Pneumatic roller completes compaction of lime-cement-flyash base at Newark Airport.

FIGURE 4-30 Vibrating roller completes compaction of subgrade in Virginia.

the surface is kept damp by sprinkling (Figure 4-31) with light rollers being used to keep the surface knitted together. In membrane curing, the stabilized soil is either (a) sealed with one shot of cutback asphalt at a rate of about 0.10 to 0.25 gal/sq yd (0.45 to 1.1 l/m^2) within 1 day after final rolling, or (b) primed with increments of asphalt emulsion applied several times during the curing period. A common practice is to apply two shots the first day, and one each day thereafter for 4 days at a total rate of 0.10 to 0.25 gal/sq yd (0.45 to 1.1 l/m^2). The type of membrane used, amount, and number of shots vary considerably. Usually, it is difficult to apply more than 0.2 gal (0.76 l) of asphalt prime because the lime-stabilized layer is relatively impervious after compaction.

MEASUREMENT AND PAYMENT

Measurement and payment considerations in the contract documents are typically incorporated in the following manner. Particular attention should be given to the water item because abnormally large quantities are used in soil-lime construction operation.

1. Method of measurement:
   a. Lime to be measured in tons;
   b. Processing of the lime-treated layer to be measured by the square yard;
   c. Water used for mixing, compacting, finishing, and curing to be measured in units of 1,000 gal; and
   d. Bituminous materials used for curing seals to be measured by the ton or gallon.
2. Basis of payment:
   a. Lime to be paid for at unit bid price per ton of material accepted in place,
   b. Processing of the lime-treated material to be paid for at the unit bid price per square yard of material completed in place,
   c. Water to be paid for at unit bid price per 100 gal of material used on the project, and
   d. Bituminous membrane to be paid for at unit bid price per ton or gallon of material used for curing purposes.

FIELD QUALITY CONTROL

Adequate quality control is essential to obtain a soil-lime mixture that will meet the stabilization objectives and provide the desired performance. There are many factors that should be considered in the quality control of soil-lime construction.

FIGURE 4-31 Moist curing of lime-stabilized subgrade in Arkansas.

Factors typically considered in soil-lime construction and procedures for field use are listed as follows.

1. Depth of lime treatment—Because lime elevates the pH of the soil, phenolphthalein, a color-sensitive indicator solution can be sprayed on the soil to determine the presence of lime (Figure 4-32). If lime is present, a reddish-pink color develops.
2. Pulverization—The degree of pulverization attained in field mixing is evaluated using selected sieve sizes. Most specifications are based on the 1-in. and the Number 4 sieves. The processed material is dry sieved to determine the percent passing. Care should be taken to ensure that the plus Number 4 material fraction is not really an agglomerated soil-lime mixture that can be easily broken down by a simple kneading action to pass the Number 4 sieve.
3. Lime spread rate—In dry lime spreading operations, the spread rate is established in terms of pounds of lime per unit area of surface. A simple procedure for measuring the actual field spreading rate is to place a 1-sq yd piece of canvas or other suitable material on the grade, and after the lime has been spread, determine the weight of lime on the 1 sq yd (Figure 4-33).
4. Slurry composition—To accurately determine the quantity of lime slurry required to provide a desired amount of lime solids, it is necessary to know the slurry composition. The most convenient method of checking lime-slurry composition is to determine the specific gravity of the slurry, either by using a hydrometer or a volumetric-weight procedure.
5. Lime content—This is specified in all soil-lime construction. An ASTM procedure (ASTM D3155–73) has been developed for determining the lime content of uncured soil-lime mixtures. The procedure is rapid and easy to conduct. Other methods of determining lime content are also used and are discussed in the proceeding section on specification references for design.
6. Density—Conventional procedures, such as sand cone, rubber balloon, nuclear,

FIGURE 4-32 Checking uniformity of mixing with phenolphthalein solution.

FIGURE 4-33 Inspector checking weight of lime with scale.

are used to determine the in situ density of compacted soil-lime mixtures (Figure 4-34). It is very important to ensure that the proper moisture-density relation for the soil-lime mixture is used in the density control operation. The moisture-density relation for a soil-lime mixture may change relative to such factors as curing time. For example, if a soil-lime layer is reworked at some later date following initial construction the maximum dry density and optimum moisture content for the mixture will probably be different from the original mixture.

7. Moisture content—Conventional procedures, oven drying, and nuclear methods (Figure 4-34) can be used for moisture determinations. In calibrating the nuclear equipment consideration should be given to the presence of the lime in the mixture.
8. Mixing efficiency—The thoroughness and efficiency of the field mixing operation is of interest. A simple procedure for evaluating mixing efficiency is as follows:
   a. Secure a sample of the field mixed soil-lime material;
   b. Halve the sample;
   c. Prepare strength specimens (unconfined strength is normally satisfactory) from one portion;
   d. Completely remix the other portion of the field mixture to ensure almost 100 percent mixing;
   e. Prepare strength specimens from the remixed material;
   f. Cure both sets of strength specimens and test them; and
   g. Calculate the mixing efficiency

   $$\text{Percentage of mixing efficiency} = \frac{\text{field mixed strength}}{\text{laboratory mixed strength}} \times 100$$

   For mixed in-place operations mixing efficiencies normally range from 60 to 80 percent. In some types of soil-lime mixing operations lower values may be acceptable.

SPECIFICATION REFERENCES

Many agencies have developed specifications and special provisions for soil-lime construction. A comprehensive listing of current specifications and special provisions is provided.

FIGURE 4-34 Determination of moisture and density with nuclear gauge in Wisconsin.

1. AASHTO—Guide Specifications for Highway Construction, 1985, (Section 307 on lime-treated subgrade).
2. AASHTO—Interim Specification for Lime for Soil Stabilization (M 216–84I) (ASTM Designation C977–83a).
3. U. S. Department of Transportation (FAA) 150/5370A. "Standard Specifications for Construction of Airports." Item P-155 of *Lime-Treated Subgrade,* May 1968.
4. U. S. Corps of Engineers. *Engineering and Design Manual—Soil Stabilization for Roads and Streets.* (Also AFM 88-7, Chapter 4), June 1969.
5. U. S. Corps of Engineers. *Guide Specification for Military Construction—Lime Stabilized Base Course, Subbase or Subgrade for Roads and Streets.* CE 807.32, December 1961 (partly revised February 1971).
6. National Lime Association. "Lime Stabilization Construction." *Bulletin 326,* 1985.
7. State specifications or special provisions for the following states: Alabama, Arizona, Arkansas, California, Colorado, Florida, Georgia, Idaho, Illinois, Iowa, Kansas, Maryland, Minnesota, Mississippi, Missouri, Nebraska, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, South Dakota, Tennessee, Texas, Utah, Virginia, Wisconsin, Wyoming, and so on.

FIELD VARIABILITY

Complete soil-lime construction will display variations in engineering properties such as strength and modulus of elasticity. This variability is typical of all field construction operations. Major factors contributing to field variability in soil-lime construction are

1. Variations in properties of the soil encountered along the grade,
2. Variability in lime spreading and distribution,
3. Variability in pulverization and mixing, and
4. Moisture and density variations in the compacted soil-lime layer.

As indicated in the section on field quality control, it is essential to monitor all aspects of soil-lime construction to assure that the desired quality of construction is secured and an acceptable level of uniformity is achieved (Figure 4-30).

SUMMARY

It is anticipated that the procedures for modern soil-lime construction described in this section will change rapidly as new pieces of equipment and new uses for lime are developed. Nevertheless, it is felt that this section provides a comprehensive summary and description of lime stabilization construction at the time this report was prepared.

References

1. M. C. ANDAY. "Curing Lime Stabilized Soils." In *Highway Research Record 29*, HRB, National Research Council, Washington, D.C., 1963, pp. 13–26.
2. R. E. GRIM. *Clay Mineralogy*. McGraw-Hill, New York, N.Y., 1953.
3. A. HERZOG and J. K. MITCHELL. "Reactions Accompanying Stabilization of Clay with Cement. "In *Highway Research Record 36*, HRB, National Research Council, Washington, D.C., 1963, pp. 146–171.
4. S. DIAMOND and E. B. KINTER. "Mechanisms of Soil-Lime Stabilization, An Interpretive Review." In *Highway Research Record 92*, HRB, National Research Council, Washington, D.C., 1965, pp. 83–102.
5. B. D. MARKS and T. A. HALIBURTON. Acceleration of Lime-Clay Reactions with Salt. *Journal of the Soil Mechanics and Foundations Division, ASCE*. Vol. 98, No. SM4, April 1972.
6. W. D. KELLER. *The Principles of Chemical Weathering*. Lucas Brothers Publishers, Columbia, Mo., 1957.
7. J. L. EADES. *Reactions of $Ca(OH)_2$ with Clay Minerals in Soil Stabilization*. Ph.D. thesis. Geology Department, University of Illinois, Urbana, 1962.
8. S. DIAMOND, J. L. WHITE, and W. L. DOLCH. "Transformation of Clay Minerals by Calcium Hydroxide Attack," *Proc., 12th National Conference on Clays and Clay Minerals*. Pergamon Press, New York, N.Y., 1964, pp. 359–379.
9. P. T. STOCKER. *Diffusion and Diffuse Cementation in Lime and Cement Stabilized Clayey Soils*. Special Report 8. Australian Road Research Board, Victoria, Australia, 1972.
10. S. DIAMOND and E. B. KINTER. Absorption of Calcium Hydroxide by Montmorillonite and Kaolinite. *Journal of Colloid and Interface Science*, Vol. 22, No. 3, 1966, pp. 240–249.
11. W. C. ORMSBY and L. H. BOLZ. Microtexture and Composition of Reaction Products in the System Kaolin-Lime-Water. *Journal of the American Ceramic Society*, Vol. 49, No. 7, 1966, pp. 364–366.
12. C. M. FORD, R. K. MOORE, and B. F. HAJEK. "Reaction Products of Lime-Treated Southeastern Soils." In *Transportation Research Record 839*. TRB, National Research Council, Washington, D.C., 1982, pp. 38–40.
13. J. G. CABRERA and C. A. NWAKANMA. "Pozzolanic Activity and Mechanism of Reaction of Red Tropical Soil-Lime Systems." In *Transportation Research Record 702*, TRB, National Research Council, Washington, D.C., 1979, pp. 199–207.
14. Z. C. MOH. "Reactions of Soil Minerals with Cement and Chemicals. "In *Highway Research Record 86*, HRB, National Research Council, Washington, D.C., 1965, pp. 39–61.
15. R. L. SLOANE. "Early Reaction Determination in Two Hydroxide-Kaolinite Systems by Electron Microscopy and Diffraction. "In *Clays and Clay Minerals, Proceedings of the 13th Conference*, Pergamon Press, New York, N.Y., 1965, pp. 331–339.
16. C. G. RUFF and C. HO. "Time-Temperature-Strength-Reaction Product Relationships in Lime-Bentonite-Water Mixtures. "In *Highway Research Record 139*, HRB, National Research Council, Washington, D.C., 1966, pp. 42–60.
17. W. H. WANG and R. L. HANDY. "Role of MgO in Soil-Lime Stabilization." In *Special Report 90: Symposium on Structure of Portland Cement Paste and Concrete*, HRB, National Research Council, Washington, D.C., 1966.

18. M. R. THOMPSON. Lime Reactivity of Illinois Soils. *Journal of the Soil Mechanics and Foundations Division, ASCE*, Vol. 92, No. SMS, Sept. 1966.
19. J. K. MITCHELL. Practical Problems from Surprising Soil Behavior. *Journal of Geotechnical Engineering, ASCE*, Vol. 112, No. 3, March 1986.
20. M. R. THOMPSON. *Factors Influencing the Plasticity and Strength of Lime-Soil Mixtures*. Bulletin 492. Engineering Experiment Station, University of Illinois, 1967.
21. C. H. NEUBAUER, Jr. and M. R. Thompson. "Stability Properties of Uncured Lime-Treated Fine Grained Soils. "In *Highway Research Record 381*, HRB, National Research Council, Washington, D.C., 1972, pp. 20–26.
22. W. G. HOLTZ. "Volume Change in Expansive Clay Soils and Control by Lime Treatment." Presented at the Second International Research and Engineering Conference on Expansive Clay Soils, Texas A&M University, College Station, Aug. 1969.
23. M. R. THOMPSON. Engineering Properties of Lime-Soil Mixtures. *Journal of Materials, ASTM*, Vol. 4, No. 4., Dec. 1969.
24. I. GOLDBERG and A. KLEIN. *Some Effects of Treating Expansive Clays with Calcium Hydroxide*. Special Technical Report 142. ASTM, Philadelphia, Pa., 1952.
25. B. J. DEMPSEY and M. R. THOMPSON. *Shrinkage and Swell Properties of Lime-Soil Mixtures*. Civil Engineering Studies, Highway Engineering Series 29; Illinois Cooperative Highway Research Program, Series 94. University of Illinois, Urbana, April 1969.
26. M. R. THOMPSON. *Soil Stabilization for Pavement Systems—State of the Art*. Technical Report. Department of the Army, Construction Engineering Research Laboratory, Champaign, Ill., March 1970.
27. S. P. MILLER, T. W. KENNEDY, and W. R. HUDSON. *Evaluation of Factors Affecting the Tensile Properties of Lime-Treated Materials*. Research Report 98–4. Center for Highway Research, The University of Texas at Austin, March 1970.
28. R. K. MOORE, T. W. KENNEDY, and J. A. KOZUH. "Tensile Properties for the Design of Lime-Treated Materials. "In *Highway Research Record 351*, HRB, National Research Council, Washington, D.C., 1971, pp. 78–86.
29. M. R. THOMPSON. "The Split-Tensile Strength of Lime-Stabilized Soils. "In *Highway Research Record 92*, HRB, National Research Council, Washington, D.C., 1966, pp. 69–82.
30. W. S. TULLOCH, II, W. R. HUDSON, and T. W. KENNEDY. *Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials*. Research Report 98–5. Center for Highway Research, University of Texas at Austin, June 1970.
31. R. F. VAN GANSE. "Immediate Amelioration of Wet Cohesive Soils by Quicklime. "In *Transportation Research Record 501*, TRB, National Research Council, Washington, D.C., 1974, pp. 42–50.
32. M. R. THOMPSON. "Shear Strength and Elastic Properties of Lime-Soil Mixtures. "In *Highway Research Record 139*, HRB, National Research Council, Washington, D.C., 1966, pp. 1–14.
33. T. E. SWANSON and M. R. THOMPSON. "Flexural Fatigue Strength of Lime-Soil Mixtures. "In *Highway Research Record 198*, HRB, National Research Council, Washington, D.C., 1967, pp. 9–18.
34. E. B. McDONALD. *Lime Research Study—South Dakota Interstate Routes. Four Year Report*. South Dakota Department of Highways, Pierre, Dec. 1969.
35. P. E. FOSSBERG. "Some Deformation Characteristics of a Lime-Stabilized Clay." In *Highway Research Record 263*, HRB, National Research Council, Washington, D.C., 1969, pp. 19–26.
36. A. A. MAXWELL and A. H. JOSEPH. "Vibratory Study of Stabilized Layers of Pavement in Runway at Randolph Air Force Base." *Proc., Second International Conference on the Structural Design of Asphalt Pavements*, University of Michigan, Ann Arbor, 1967.
37. R. K. MOORE and T. W. KENNEDY. *Tensile Behavior of Subbase Materials Under Repetitive Loading*. Research Report 98–12. Center for Highway Research, The University of Texas at Austin, Oct. 1971.
38. M. J. DUMBLETON. *Investigations to Assess the Potentialities of Lime for Soil Stabilization in the United Kingdom*. Technical Paper 64. Road Research Laboratory, England, 1962.
39. B. J. DEMPSEY and M. R. THOMPSON. "Durability Properties of Lime-Soil Mixtures." In *Highway Research Record 235*, HRB, National Research Council, Washington, D.C., 1968, pp. 61–75.
40. M. R. THOMPSON and B. J. DEMPSEY. "Autogenous Healing of Lime Soil Mixture." In *Highway Research Record 263*, HRB, National Research Council, Washington, D.C., 1969, pp. 1–7.
41. E. B. McDONALD. *Experimental Stabilization Expansive Shale Clay—Lyman County. Four Year Report*. South Dakota Department of Highways, Pierre, 1969.
42. Quicklime Stabilizes Canal Lining. *Roads and Streets* (*California*), Jan. 1975.
43. K. A. GUTSCHICK. *Lime Stabilization Under Hydraulic Conditions*. 4th International Lime Congress, Hersey, Pa., Sept. 21, 1978.
44. K. A. GUTSCHICK. Canal Lining Stabilization Proves Successful. *Pit and Quarry*, May 1985.
45. T. K. LIU and M. R. THOMPSON. "Variability of Some Selected Laboratory Tests." *Proc., National*

Conference on Statistical Quality Control Methodology in Highway and Airfield Construction, University of Virginia, Charlottesville, Nov. 1966.

46. B. P. MARSHALL and T. W. KENNEDY. *Tensile and Elastic Characteristics of Pavement Materials.* Research Report 183–1. Center for Highway Research, University of Texas at Austin, Jan. 1974.
47. C. McDOWELL. "An Evaluation of Soil-Lime Stabilization Mixtures. "In *Highway Research Record 139*, HRB, National Research Council, Washington, D.C., 1966, pp. 15–24.
48. C. McDOWELL. "Design and Construction of Subbases and Foundations for Pavements." In *Transportation Research Record 537*, TRB, National Research Council, Washington, D.C., 1975, pp. 31–43.
49. C. McDOWELL. "Development of Lime Stabilization for Improvement of Load Capacities of Pavements." Presented at 29th Annual Highway Short Course, Texas A&M University, College Station, March 29–April 1, 1955.
50. C. McDOWELL. *Flexible Pavement Design Guide.* Bulletin 327. National Lime Association, Arlington, Va., 1972.
51. C. McDOWELL. "Progress of Lime Stabilization in Texas." Presented at the Annual Convention of the National Lime Association, Arlington, Va., May 23–25, 1960.
52. C. McDOWELL. "Stabilization of Soils with Lime, Lime Fly Ash, and Other Lime Reactive Materials." *Bulletin 231*. HRB, National Research Council, Washington, D.C., 1959, pp. 60–66.
53. "A Laboratory and Field Investigation of Some Virginia Soils for Lime Stabilization." Presented at ASTM Soil Testing Symposium, June 1967.
54. E. B. McDONALD. *Experimental Stabilization of the Pierre Shale, Project F 039–1(1) Lyman County, South Dakota. Final Report.* South Dakota Department of Highways, Pierre, April 1969.
55. E. B. McDONALD. *Lime Research Study—South Dakota Interstate Routes (Sixteen Projects).* South Dakota Department of Highways, Pierre, Dec. 1969.
56. R. L. TERREL, J. A. EPPS, E. J. BARENBERG, J. K. MITCHELL, and M. R. THOMPSON. *Soil Stabilization in Pavement Structures—A User's Manual. Volume 1, Pavement Design and Construction Considerations.* Report FHWA–IP–80–2. FHWA, U.S. Department of Transportation, Oct. 1979.
57. R. L. TERREL, J. A. EPPS, E. J. BARENBERG, J. K. MITCHELL, and M. R. THOMPSON. *Soil Stabilization in Pavement Structures—A User's Manual. Volume 2, Mixture Design Considerations.* Report FHWA–IP–80–2. FHWA, U.S. Department of Transportation, Oct. 1979.
58. J. L. EADES and R. E. GRIM. "A Quick Test to Determine Lime Requirements for Lime Stabilization." In *Highway Research Record 139*, HRB, National Research Council, Washington, D.C., 1966, pp. 61–72.
59. M. R. THOMPSON and J. L. EADES. Evaluation of Quick Test for Lime Stabilization. *Journal of the Soil Mechanics and Foundation Division, ASCE*, Vol. 96, No. SM2, March 1970.
60. J. R. HARTY. *Factors Influencing the Lime Reactivity of Tropically and Subtropically Weathered Soils.* Ph.D. thesis. Department of Civil Engineering, University of Illinois, Urbana, 1970.
61. M. R. THOMPSON. "Suggested Method of Mixture Design Procedure for Lime-Treated Soils. "In *Special Technical Publication 479: Special Procedures for Testing Soil and Rock for Engineering Purposes*, ASTM, Philadelphia, Pa., 1970.
62. L. W. LOCKETT and R. K. MOORE. "Lime-Soil Mixture Design Considerations for Soils of Southeastern United States." In *Transportation Research Record 839*, TRB, National Research Council, Washington, D.C., 1982, pp. 20–25.
63. F. C. TOWNSEND and R. T. DONAGHE. *Investigation of Accelerated Curing of Soil-Lime and Lime-Fly Ash-Aggregate Mixtures.* Technical Report S–76–9. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., Aug. 1976.
64. T. M. PETRY, C. J. ARMSTRONG, and D. T. CHANG. "Short-Term Active Soil Property Changes Caused by Injection of Lime and Fly Ash. "In *Transportation Research Record 839*, TRB, National Research Council, Washington D.C., 1982, pp. 26–32.
65. J. R. BLACKLOCK and C. H. LAWSON. *Handbook for Railroad Track Stabilization Using Lime Slurry Pressure Injection.* Report FRA/ORD–77/30. Federal Railroad Administration, Office of Research and Development, Washington, D.C., 1977.
66. J. R. BLACKLOCK. *Evaluation of Railroad Lime Stabilization.* Report FRB/ORD–78/09. Federal Railroad Administration, Office of Research and Development, Washington, D.C., 1978.
67. J. R. BLACKLOCK. "Lime Slurry Glaze Method of Soil Testing." Presented at ASCE Specialty Conference on Grouting in Geotechnical Engineering, New Orleans, Louisiana, Feb. 1982.
68. J. R. BLACKLOCK, R. C. JOSHI, and PAUL J. WRIGHT. "Pressure Injection Grouting of Landfills Using Lime and Fly Ash." Presented at ASCE Specialty Conference on Grouting in Geotechnical Engineering, New Orleans, Louisiana, Feb. 1982.
69. R. S. BOYNTON and J. R. BLACKLOCK. *Lime Slurry Pressure Injection Bulletin.* Bulletin 331. National Lime Association, Arlington, Va., 1985.

70. Q. L. ROBNETT, G. S. JAMISON, and M. R. THOMPSON. *Technical Data Base For Stabilization of Deep Soil Layers*. Technical Report AFW2–TR–70–84. Air Force Weapons Lab, Kirtland AFB, New Mexico, April 1971.
71. P. J. WRIGHT. Lime Slurry Pressure Injection Tames Expansive Clays. *Civil Engineering*, Oct. 1973 and July 1974.
72. Novel Lime Slurry Plant Streamlines Stabilization. *Rural and Urban Roads* (*Texas*), March 1971.
73. Latest Slurry Methods Aid Quicklime Stabilization. *Highway and Heavy Construction*, Sept. 1983.